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Editorial

Racquet sports continue an unstoppable rise in the sporting world in many aspects, such as the number of players, events and, of course, scientific research. This rise has to do with the increase in the sporting life of great players; which, in turn, is a product of the growth of scientific literature and its application to training. In this sense, we can cite as an example the current retirement of Roger Federer at the age of 41, a fact that a few decades ago would have been unlikely. And it is not the only case since the Spaniard Rafael Nadal continues to win titles despite his advanced age for sport.

There may be many and varied reasons for this “longevity” effect in racket sports, but without a doubt, the increase in human and technological resources, transferred from scientific research, is undoubtedly one of them. And in this sense, the International Journal of Racket Sports Science continues to offer knowledge and experience from all continents to contribute to this growth.

This issue is a tangible example of this fact. In this sense, systematic reviews allow us to have a map of the research in a subject, a useful aspect not only for researchers but also for technical teams. And in the present issue, two are presented, related to sports injuries, one by Larsson and collaborators, and the other by Fahlström and Zeisig, both of which focus on lower or upper limbs, analysing racket sports globally, allowing notes and similarities that help the coach in the key points in the prevention of these target injuries in these sports modalities.

At the same time, the current importance of technological advances has been highlighted, which are facilitating the analysis of data for diagnostic and training purposes in the athlete, as is the case with the contribution in this issue of Gawin et al. with an interesting contribution of a sensor integrated in the badminton racket (Oliver® Plasma TX 5), as an added value of the observational methodology. As well as the importance of the analysis of technique by means of advanced technology, such as the study by Ruiz-Malagón et al., analysing the biomechanical differences in the technical gesture of the one-handed and two-handed backhand, which has a direct application in the teaching-learning process in players in training.

Therefore, for yet another issue, the International Journal of Racket Sports Science continues to provide research and scientific evidence that has a direct impact on the technological and human progress of technical teams in racket sports.

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Evaluation of a Freely Available Sensor Racket as a Diagnostic and Training Tool in Elite Badminton

Evaluación de una raqueta con sensor disponible comercialmente como herramienta de diagnóstico y entrenamiento para bádminton de élite

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Abstract

To avoid the drawbacks of optical video-based motion capture systems and due to the ongoing miniaturization of integrated sensors, an increasing variety of sensor-based systems has been used for motion capture in sports. Meanwhile, there are ready-made, commercially available solutions that claim to be capable of recording reliable kinematic data. This research project focuses on the question of whether a commercially available badminton racket with an integrated sensor device (Oliver® Plasma TX 5) provides meaningful data for diagnostic and training purposes in elite sports. Therefore, 16 elite badminton players executed jump smashes using this sensor racket while the kinematics of the stroke technique were recorded using a high speed video-based system. Bland-Altman plots were applied to analyze the agreement between the two systems. The plots revealed a systematic bias and 95% limits of agreement ranging from 6% to 23%: The detection of stroke techniques showed a 42% rate of success. These data show that the measurement accuracy of the sensor racket is not sufficient for use in diagnostics or training. Future development of the sensor racket could include a method to calibrate the system prior to a measurement, in addition to correcting the underlying algorithm to reduce the bias.

Keywords: *Inertial sensor systems, movement analysis, racket sports, badminton.*

Resumen

Para evitar las desventajas de los sistemas ópticos de captura de movimiento basados en video y debido a la continua miniaturización de los sensores integrados, una creciente variedad de sistemas basados en sensores se ha usado para la captura de movimiento en deportes. Entretanto, existen soluciones ya terminadas y comercialmente disponibles que afirman ser capaces de registrar datos cinemáticos confiables. Este proyecto de investigación se enfoca en la pregunta de si una raqueta de bádminton disponible comercialmente con un sensor integrado (Oliver® Plasma TX 5) proporciona datos relevantes para el diagnóstico y entrenamiento en deportes de élite. Por tanto, 16 jugadores de bádminton de élite ejecutaron remates en salto usando la raqueta con sensor mientras la cinemática de la técnica del golpe era grabada con un sistema de alta velocidad basado en video. Los gráficos de Bland-Altman se usaron para analizar la concordancia entre los dos sistemas. Los gráficos revelaron un sesgo sistemático y límites de concordancia del 95% entre 6% y 23%. La detección de las técnicas del golpe evidenció una tasa de éxito del 42%. Estos datos demuestran que la precisión en la medición de la raqueta con sensor no es suficiente para usarla en diagnóstico o entrenamiento. El desarrollo futuro de la raqueta con sensor podría incluir un método para calibrar el sistema antes de hacer una medición, además de corregir el algoritmo subyacente para reducir el sesgo.

Palabras clave: *Sistema de sensor inercial, análisis del movimiento, deportes de raqueta, bádminton.*

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INTRODUCTION

When facing the task of conducting valid movement analyses, the high movement velocities in most sports are challenging. The use of optical video-based motion capture systems, for example, is usually accompanied by some crucial constraints, i. e. the necessity of a high sampling rate, the large data volume when using high frequency systems, the confined spatial frame, and the large effort required to extract the kinematic data (Krüger & Edelmann-Nusser, 2010; Wang et al., 2016). To minimize these drawbacks, and due to the ongoing miniaturization of integrated sensors, an increasing variety of sensor-based systems has been developed and used for motion capture in sports (e.g., Gawin, 2010; Jaitner & Gawin, 2010; Pei et al., 2017). In this context, the question arises whether these sensor systems provide the same accuracy and reliability as extensive optical video-based analyses. Taha, Hassan, Yap and Yeo (2016) combined an integrated sensor unit and the Kinect depth sensor that utilizes infrared light for motion capture. The kinematics of a subject's wrist movements while executing badminton smash movement patterns with the upper limb were recorded simultaneously by the two systems. Even though the measured average accelerations differed between the two systems, the authors concluded that the outcome patterns revealed by the Kinect depth sensor were comparable to the values of the integrated sensors.

Another attempt to compare a sensor-based system and a common video-based system is a study by Kerner and Witt (2013). To test the usability of a sensor-based whole-body system (Xsens Technologies, https://www.xsens.com/) for kinematic analyses, somersault movements of a female gymnast were recorded using this system and synchronously videotaped using a common videometry system (Simi Motion, http://www.simi.com/de/home.html). A strong deviation between the two systems from 30% up to 43% was revealed for the center of gravity of the athlete´s body and the amplitudes of the arm movement velocities.

The analysis of movements in the racket sport badminton is also characterized by high movement velocities, especially when the shuttle, the racket, and the upper body segments are addressed (e. g., Kwan et al., 2011; Tsai & Chang, 1998). In elite badminton, shuttle velocities of approximately 100 m/s and racket speeds of more than 50 m/s were reported (Jaitner & Gawin, 2010; Kwan et al., 2011). A manufacturer of racket sport equipment has reported an initial shuttle speed of 116.9 m/s (Yonex Corporation, 2010). This value was recorded, while an international top player executed jump smashes, the stroke technique in badminton, where the highest shuttle velocities are generated (Tsai & Chang, 1998). When performing a jump smash, a player hits the shuttle as hard as possible downwards into the opponent´s court while airborne after a jump. The aim is to generate the highest possible shuttle velocity.

Because of these high movement velocities, there have been many possible solutions generated to obtain kinematic data using different sensor-based measurement systems in the field of badminton. Jaitner and Gawin (2010) developed a mobile measurement device to analyze the movements of the racket arm and the racket (Jaitner & Gawin, 2007, 2010). The usability of the mobile device that was based on two-dimensional piezoelectric accelerometers (working at a sample rate of 1000 Hz) that were attached to the racket arm and racket was evaluated using a three-dimensional high-frequency video system (Basler, sample rate 250 Hz, https://www.baslerweb.com/). The comparison between the obtained high-frequency video data and the values from the accelerometers revealed moderate correlations between the acceleration of the racket arm and the racket with the shuttle velocities (Jaitner & Gawin, 2010). The reliable recording of exact position data by the sensor based system, however, was not possible, because the utilized technology only included 2D-accelerometers, no gyroscopes and no magnetic field sensors.

Other approaches to determine kinematic or performance parameters using various sensor measurement set-ups were, for example, the combination of high-frequency videometry and strain gauges at the racket (Kwan et al., 2010; Kwan & Rasmussen, 2010), inertial sensors (Kiang et al., 2009; Wang et al., 2016), acoustic sensors (Kiang et al., 2009) or electrocardiographic equipment (Sakurai & Ohtsuki, 2000; Tsai et al., 2006; Tsai, Huang, et al., 2005; Tsai, Yang, et al., 2005, for an overview see Wang et al., 2016).

Meanwhile, in the follow-up of these scientific attempts to develop and evaluate reliable measurement devices for movement analysis in racket sports, there are now ready-made commercially available solutions. One example in badminton is a sensor racket made by Oliver (Plasma TX 5, https://www.oliver-sport.de/plasma-tx5-rds/). An inertial sensor unit has been integrated into the grip of this racket (figure 1) to record velocities, recognize stroke techniques, and measure physical activity.

This racket with the integrated sensor succeeded in matching the weight (88 g.), balance, and price of common badminton rackets without integrated sensors. The balance remains unaffected by the sensor unit, as the weight of the replaced grip material is similar to the weight of the sensor unit.

Regarding the difficulties determining valid kinematic data in the sport of badminton, the recent research project focuses on whether the output of the above-mentioned sensor racket agrees with high speed video data. The measurement of valid velocities would be a valuable tool for performance analysis in the training process of skilled badminton players.

Figure 1. The sensor unit applied to the racket grip after cover has been removed.

METHODS

Sample

Sixteen highly skilled male badminton players (age 23.56 ± 4.63 years), all members of the German national team and without exception experienced in national and international competitions, participated in this study.

Instruments

The aim was to compare the inertial sensor racket by Oliver® with an approved method for obtaining kinematic data – in the current project an optical video-based camera system consisting of two industrial high-speed cameras (Optronis, Kehl, Germany, https://optronis.com/machine-vision/). These cameras are capable of recording video footage with a sampling rate of up to 16,000 Hz. For this study the cameras were adjusted to 500 Hz. This system allows the three dimensional capture of badminton stroke techniques with a sufficient sampling rate and high accuracy. For an evaluation of this method see Gawin, Beyer, Büsch and Høi (2012).

The variables that were recorded by the video system were shuttle and the racket velocities at the time of impact and racket angle (in relation to the horizontal plane) at impact. The core of the inertial sensor system consisted of a three axis accelerometer and gyroscope (figure 2). The recorded data were transferred in real time via Bluetooth® to a mobile device (smartphone, Samsung X-Cover) that was positioned near the court. The mobile device calculated and displayed the results in the system software Smart Badminton (Coolang, Shenzhen, China).

The variables of interest collected by the inertial system were velocity, stroke technique, and angle. As, unfortunately, the software manual does not provide information as to which velocity and angle are calculated, we contacted the manufacturer and were told that the computed variables represent racket velocity and racket angle at impact. However, the sampling rate is unknown.

Study Design and Implementation

Each participant performed a standardized 10-minute warm up. After the warm up, twelve jump smashes after single serves by an opponent were executed (figure 2).

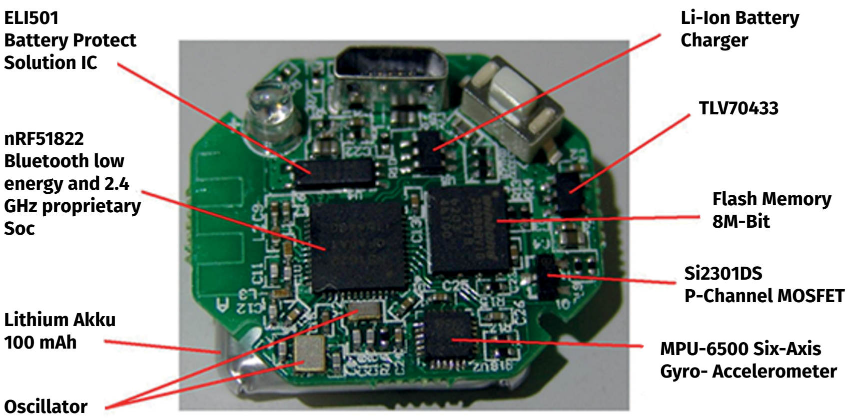

Figure 2. The board with sensor components in the racket grip.

Each subject used the sensor racket Plasma TX 5 for the smashes. After every stroke, the mobile device displayed the velocity, angle, and stroke technique. This data was notated immediately after every smash. Simultaneously, the execution of each smash was recorded by the high frequency camera system from two perspectives. The cameras were positioned at an angle of about 90° to each other beside the court.

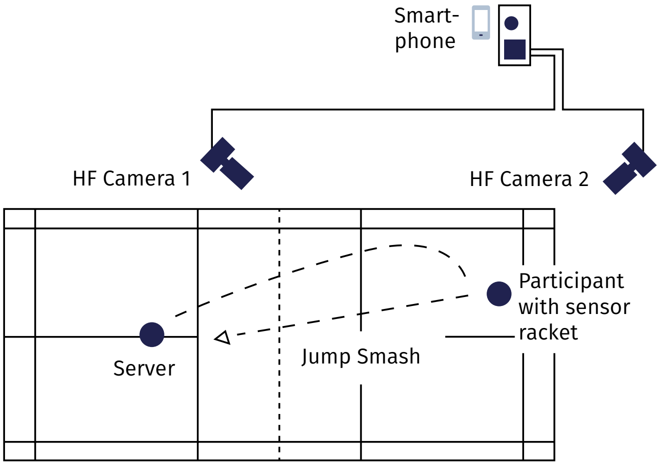

Figure 3. Experimental set up.

Variables

Using the video footage, shuttle and racket velocities, as well as the racket angle in relation to the horizontal plane were calculated. The kinematic variables obtained by the high frequency camera system were obtained by tracking the racket and the shuttle manually using the software Simi Motion for the analysis of 3D video data (Simi Reality Motion Systems, Germany).

The calculated variables had to meet certain criteria to provide comparability to similar studies. For shuttle speed, the temporal space that is utilized to calculate the speed is crucial, because the shuttle velocity decreases dramatically only ms after impact. According to former studies (Gawin et al., 2012), the time interval to compute the shuttle velocities was 12 ms immediately after impact. Shuttle velocity was averaged over this time interval.

As far as racket speed is concerned, the time frame comprised ten ms, beginning eight ms before and ending two ms after impact - a time interval within which the racket usually reaches its highest speed (Jaitner & Gawin, 2010; Kwan et al., 2011). Racket speed was calculated every two ms beginning eight ms before impact. The reference point for the measurement of racket speed was the t-joint. The obtained values were smoothed by the moving average over three frames, and then the highest speed in this ten ms interval was used to compare the two kinematic measurement systems.

The racket angle is the inclination of the racket (using the t-joint and the lowest point of the grip) in relation to a theoretical horizontal plane through the lowest point of the grip.

Statistics

Bland-Altman-Plots were established (Bland & Altman, 1986; Bland & Altman, 1999) to compare the two different methods. Bland-Altman-Plots serve to discover the differences between two methods that are to be compared by plotting the differences of the paired data against the mean values of the data tuples. To express the size of the deviation, limits of agreement must be computed that, following the definition by Bland and Altman, confine an interval within which 95 % of the differences between the two methods are expected to lie (Bland & Altman, 1999). In general, limits of agreement (LoA) are analysed in a graphical manner using Bland-Altman-Plots, where the difference between the two methods is plotted against their average as a point cloud. The point cloud is accompanied by lines indicating the average difference between methods (bias), as well as the upper and lower limits of agreement between the two methods.

Since we obtained several repeated trials per subject, we applied the method described by Bland & Altman (Bland & Altman, 2007) to compute limits of agreement for repeated measurements within subjects, as well as the "conventional" LoA method of deviations between methods for the average trial of each subject. If a relationship was found between the differences and the magnitude of the measurement, the LoAs were calculated using a linear regression approach for non-constant differences across the range of measured values (Bland & Altman, 1999).

The calculation of the LoAs itself provides no information about the significance of disagreement between methods. A sufficient amount of agreement has to be defined prior to the measurement. In this study, a deviation of no more than 5 % was defined as adequate for the useful application of the inertial measuring system for diagnostic and training purposes. Since Bland-Altman plots were used, this limit was calculated on the basis of the average values. The average values reached a maximum of 43.49 m/s for the racket velocities, and a maximum racket angle of 101.43°. This resulted in defined maximum limits of agreement of no more than 2.67 m/s for the racket velocities, and 5.07° for racket angle, respectively, based on the assumption that the maximal deviation does not exceed 5 %. LoA analyses and plots were created using R 3.4.2 (R_Core_Team, 2017).

RESULTS

The overall mean of the shuttle velocities counted for 84.14 m/s (±5.72 m/s) with a maximum of 100.35

m/s and a minimum of 67.10 m/s. The individual mean values for each subject are depicted in figure 4.

Figure 5 shows the differences-plot of the individual and average values for each subject for racket velocities. This plot reveals a clear relationship between the differences and the magnitude of the measurement. The underlying algorithm to calculate racket speed and angle was not able to correct these deviations.

As expected, the single values show a broader variance, with LoAs of ±10.05 m/s, than the average values, with LoAs of ±7.10 m/s. However, both LoAs are not acceptable, because they exceed the defined maximum deviation of 5 %.

It should be mentioned that the regression line changed its direction when averaging the single values. This is because the outlying single values are smoothed by the calculation of the players´ average values.

For the racket angle at impact, the interval between the limits of agreement was smaller, with a range of ±12.21° for the single values and ±6.41° for the means, respectively (figure 6). These are intervals that nearly meet the required limit of 5.07° that depicts a deviation of 5 %.

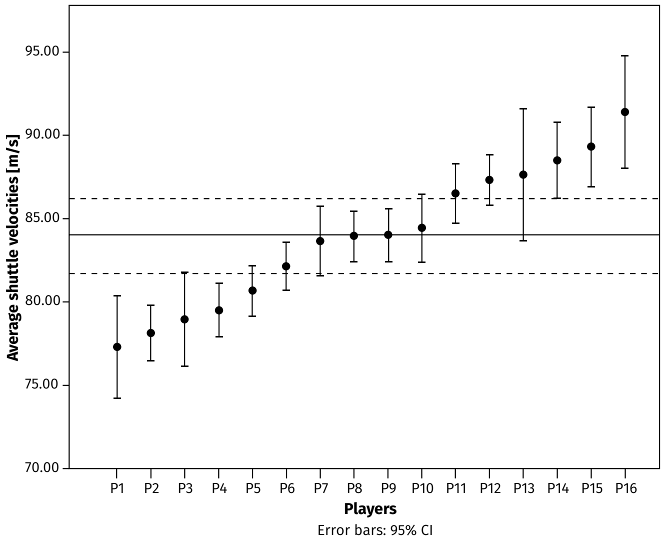

Figure 4. Average shuttle velocities.

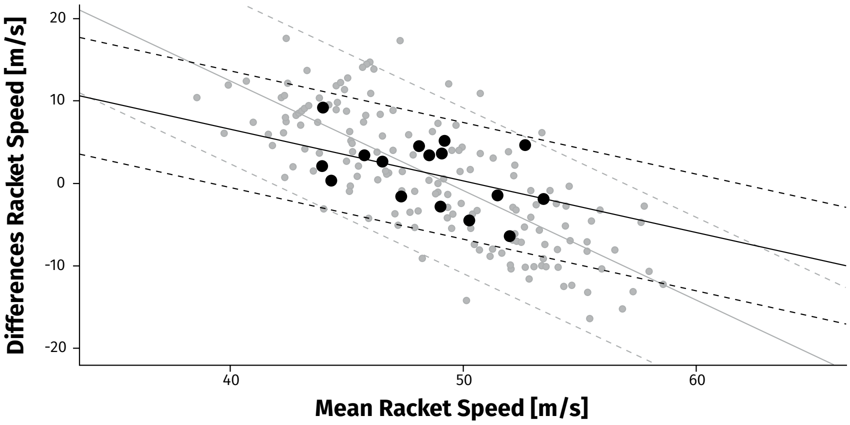

Figure 5. Plot of the differences (camera – sensor) against the average of the data tuples camera – sensor for the racket speeds. The black dots depict the mean values of each player, the light grey dots the single values.

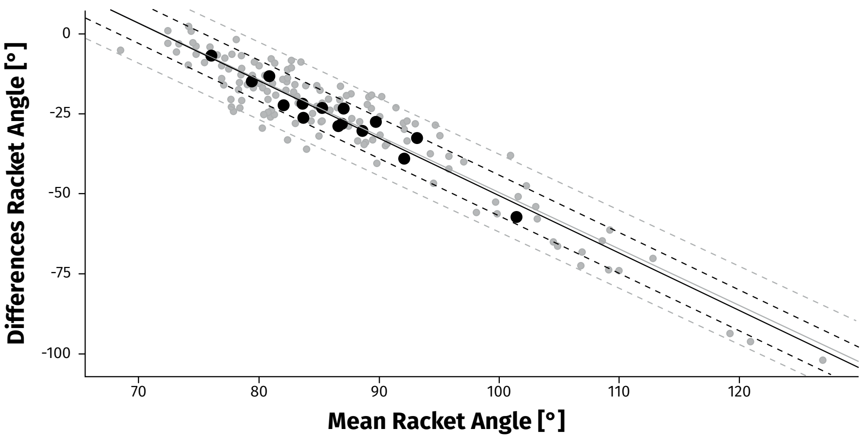

Figure 6. Plot of the differences (camera – sensor) against the average of the data tuples camera – sensor for the racket angle. The black dots depict the average values of each player, the grey dots the single values.

Concerning stroke techniques, the sensor racket detected four different kinds of strokes instead of just one, although the participants consistently performed smashes. The sensor racket correctly sensed the stroke type in 40.33 % of all recorded trials, but did not in 59.67 % of the trials.

DISCUSSION

The aim of evaluating the badminton sensor racket was to analyze the agreement between a standard video-based motion capture system and an integrated sensor system with regard to the latter's practical application as a diagnostic or training device.

When attempting to recognize stroke techniques, the sensor racket had a success rate of about 40 %, which is not sufficient for any practical use. As Pei and colleagues (Pei et al., 2017) have shown in tennis, the stroke technique detection bases on the course of the accelerometric data and has a highly specific event detection algorithm. A closer look to the stroke technique categories in the software of the analyzed racket reveals that there are techniques listed that are much more common in tennis, like slice or block, and other significant badminton stroke techniques are missing, like all kind of backhand stroke techniques. It is thinkable that the software of the sensor racket was not specifically designed for badminton. This could be a possible explanation for the poor recognition rate of the sensor racket.

For the variables racket speed and racket angle, the sensor racket results contain systematic bias and poor agreement to the camera system. The 95-%-limits of agreement range from ±16 % to ±23 % for racket velocities, and from about ±6 % to ±12 % for racket angles, respectively. The lower values depict the averaged, and the higher values the single performance values of each participant. As expected, the calculation of averages reduced the impact of the outliers and led to smaller LoAs and better agreement between the methods.

However, the agreement between the two systems for the average recordings for each player was insufficient for any practical application, even if the limits of agreement for the racket angles came close to meeting the demanded criteria. From a practical point of view, however, it is worth discussing how calculating racket angle can be used in a beneficial way by coaches or players when performing a smash.

Possible reasons for these between-subject deviations could be the grip position in the player´s racket hand, and the tendency of accelerometers to overestimate measurement (Alanen et al., 2021). Usually, highly skilled players use a very stable grip technique, especially in a highly automatized and fast movement technique like the jump smash. However, there are slight between-subject differences in the allocation of the racket grip in the hand within a group of players, deviating a few degrees from each other. If the alignment of the grip and therefore the orientation and the angle of the racket deviates between players, the axes of the accelerometer in the grip will also have a different orientation between the players, and will be subject to different amounts of cross-talk. Very likely the analyzed sensor unit will not be capable to successfully eliminate this cross-talk when calculating the velocities because of the complex algorithms to obtain velocities from accelerometric raw data. These algorithms have to imply three dimensional integrating of the accelerometric signals, calculating the inclination of the device by the gyroscopes to separate rotational from translational movements and filtering noise in real time. For these calculations a computing power is afforded that most probably the sensor of the analyzed racket will not provide. According to our results the comparison of independent subjects is not possible with the given sensor system.

A valuable future development of the sensor-based system could be a method that enables the user to individually calibrate the system and setting all signals to zero prior to a measurement, to reduce noise and cross-talk. However, it is not likely that an individual calibration would fix the problem of the strong relationship found between the differences and the magnitudes of the measurements. A correction of the system software, the sensor architecture and the underlying algorithm seems to be necessary.

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A narrative review of Achilles tendon ruptures in racket sports

Revisión narrativa de las roturas de tendón de Aquiles en deportes de raqueta

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Abstract

This review aims to report the existing research about Achilles tendon ruptures (ATR) in racket sports. Further, this narrative review will also include the acute management, rehabilitation, treatment and prognosis of an ATR. ATR is a common injury among individuals playing racket sports, however, the literature is limited and not up to date. Previous research claims that up to 70 percent of all ATR is related to sports activities where racket sports dominate. A large number of patients sustaining an ATR return to sport within a year from injury.

Keywords: *Achilles tendon ruptures, ATR, Racket Sports, Badminton, Tennis, Padel, Sports injuries.*

Resumen

Esta revisión pretende cubrir la investigación existente sobre las roturas del tendón de Aquiles (RTA) en los deportes de raqueta. Adicionalmente, esta revisión narrativa también incluirá el manejo agudo, la rehabilitación, el tratamiento y el pronóstico de una RTA. La RTA es una lesión común entre individuos que practican deportes de raqueta, sin embargo, la literatura es limitada y no está actualizada. Investigaciones previas afirman que hasta el 70% de todas las RTA están relacionadas con actividades deportivas donde predominan los deportes de raqueta. Un gran número de pacientes que sufren RTA regresan al deporte en el plazo de un año desde la lesión.

Palabras clave: *Rotura del tendón de Aquiles, deportes de raqueta, bádminton, tenis, pádel, lesiones deportivas.*

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INTRODUCTION

A middle-aged man is playing tennis at the tennis court. He just took a step back, awaiting a long ball, when he realizes that the ball is a drop shot, closer to the net. In an effort to reach the ball, he pushes off quickly and experiences a pop with immediate pain in the back of the calf, as though he was struck from behind, the Achilles tendon ruptured.

Achilles tendon rupture (ATR) is a common injury in both elite and recreational sports, that may lead to reduced function and activity level in the long-term (Tarantino et al., 2020). The incidence of ATR is increasing, where males are overrepresented with a ratio of 4:1 compared to females (Huttunen et al., 2014). The reason for this skewed distribution between the sexes is unknown. Racket sports are common activities for those rupturing their Achilles tendon (Houshian et al., 1998) however, research concerning specific racket sports in relation to acute ATR is limited.

The diagnosis of an acute ATR is clinical, meaning that the diagnosis can be determined by a patient interview and physical examination. The treatment for an acute ATR could be either surgical or non-surgical, followed by rehabilitation. There is an ongoing debate whether the advantages of each treatment outweigh the disadvantages. The difficulties with non-surgery compared with surgery are that re-ruptures occur more frequently, and also the tendon may undergo excessive elongation. Conversely, surgical intervention is associated with problems such as surgical site infection, adhesions, sural nerve injuries and other wound problems.

The Achilles tendon requires between six to twelve months to heal and remodel after an acute ATR. The recovery phase (6-12 months) after the injury includes supervised physiotherapy which is of importance for both the rehabilitation and to improve physical activity, functional outcome and return to sport (Holm et al., 2014; Zhang, et al., 2021).

INCIDENCE, CLINICAL FINDINGS AND DIAGNOSIS

Over the last few decades, epidemiological studies have reported increasing incidence of ATR (Huttunen et al., 2014; Ganestam et al., 2016). Between 1994 and 2013, the incidence of ATR increased from 27.0 to 31.2 ruptures/100,000 inhabitants/year in Denmark (Ganestam et al., 2016). In Sweden - between 2001 and 2012 - it has been reported an increase from 47.0 to 55.2 per 100,000 person-year in the incidence of men. The corresponding increase for women were 12.0 to 14.7 per 100,000 person-year (Huttunen et al., 2014). Thus, increasing numbers of males sustain ATR compared with females. Additionally, the median age at the time of injury is also increasing (Huttunen et al., 2014). A proposed explanation for the increasing incidence and median age is the growing interest in participating in recreational sport in the older age group (Huttunen et al., 2014; Ganestam et al., 2016).

The reported mechanisms of the injury are usually a characteristic for an acute ATR. Often, the injury occurs without any warning symptoms. A sudden dorsiflexion of the ankle or a "acceleration-deceleration mechanism" is a common description of the movement that caused the injury (Tarantino et al., 2020).

Clinical examination, including sensitive clinical tests, may be considered to be the golden standard to diagnose acute rupture and is more sensitive than ultrasonography (Maffulli, 1998). Simmonds' or Thompson's test (Fig 1) (Thompson, 1962), also called "calf squeeze test", is performed with the patient in prone position with their feet hanging over the edge of the examination couch. The examiner squeezes the calf muscle, which mimics a muscle contraction, and during normal circumstances this causes passive ankle plantarflexion. If the tendon is ruptured, no plantarflexion of the ankle will occur when squeezing the calf muscle, termed a positive test. There are cases when the tendon from the plantaris muscle is intact which could give a false negative sign and therefore, it is of importance to also perform Matles´ test (Fig 2) (Matles, 1975). When performing Matles' test (Matles, 1975), the patient is also in prone position but the knees are bent to 90°. The uninjured ankle will be in a slight plantarflexed position while, with a ruptured tendon, the injured ankle will fall into an increased dorsiflexion.

Magnetic Resonance Imaging (MRI) or ultrasound (US) is not recommended for diagnosing an acute ATR in order to undermine the risk of missing patients with an acute ATR. However, US is recently introduced for treatment choice since the gap between the distal and proximal part of the tendon influence the outcome of respectively treatment (Westin et al., 2016). It is of importance to know that US is highly operator-dependent and that the subsequent evaluation of both still and video images can be challenging and a limiting factor.

ACHILLES TENDON RUPTURES IN RACKET SPORTS

A definite correlation between an injury and a particular sport is rare to find, however, there are several articles that show an association between racket sports and acute ATR. Houshian et al. (1998) showed that between 1986-1996, 70% of the ATR in Denmark were associated with sport activities. The most common sport activities were badminton, soccer and handball (Houshian et al., 1998). In another Danish study, performed on 39 badminton players sustaining an Achilles tendon rupture, 87% of the ruptures occurred towards the end of the game or in the middle. Furthermore, the authors concluded that tiredness or fatigue during racket sport was a predictor for an ATR (Kaalund et al., 1989). Other studies have shown that ATR forms 6.9-9% of acute tennis injuries (Raikin et al., 2013; Lemme et al., 2018) and 3-8.7% of acute badminton injuries (Fahlström, 2010). The incidence of ATR in padel, squash and lacrosse are not known.

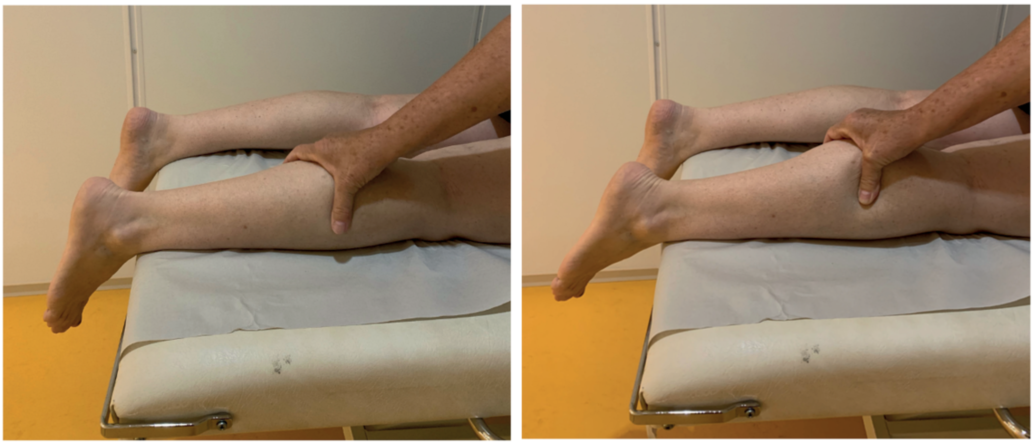

Figure 1. Thompsons test with a negative result (no rupture in the Achilles tendon). If no plantarflexion occur during the squeeze the result in positive.

Figure 2. Matles' test. In the left picture the ankle has an anatomic angle compared to the right where the dorsiflexion of the ankle is increased which is an indirect sign of an Achilles tendon rupture.

TREATMENT OF AN ACHILLES TENDON RUPTURE

When it is suspected that a player has suffered an ATR on the racket sport court, the best treatment for the tendon is to immobilise the injured ankle in a plantarflexed position and help the player to an appropriate medical facility for assessment, diagnosis and management planning. The player should not be weight baring on the injured limb and if available and familiar with crutches these may be used.

Patients that suffer from an acute ATR can receive either surgical or non-surgical treatment and there is no consensus that one method is superior to the other. Several randomized controlled studies (RCTs) and meta-analyses have been published but the outcomes of these differ. In summary, re-ruptures are more frequent in non-surgically treated patients while surgical wound problems and sural nerve injury are complications relating only to surgically treated patients (Deng et al., 2017; Khan et al., 2005; Soroceanu et al., 2012; Nilsson-Helander et al., 2010). The re-rupture rate in non-surgical treated patients has been considered to be reduced if functional rehabilitation, including early weight-bearing, is incorporated (Beyer et al., 2015; Wu et al., 2016; Zhang et al., 2015). The differing findings from RCTs have led to a general paradigm shifts for the standard treatment tending to move towards non-operative treatment. Even though there are many guidelines to the selection of a treatment regimen, the final decision should be based on a patient's individual factors and preferences.

Non-surgical treatment may involve a cast or a walker brace, keeping the ankle in approximately 30° plantar flexion. After 2 weeks, if a cast has been used, it will be replaced by a walker brace with 3-4 wedges (Fig 3) that keeps that ankle in a slight plantar flexion. Also, 2 weeks after the injury, supervised physiotherapy should be introduced. The wedges will be gradually removed one by one during 6 weeks, and after 8 weeks allowing a neutral position of the ankle.

Figure 3. A walker brace with wedges.

Several surgical techniques are described and are in general sub-divided into open, mini-invasive and percutaneous. Repairs may be performed with endoscopically assisted surgery or with ultrasonographic guidance. Techniques using smaller incision known as minimally-invasive have been developed to minimize wound related problems however, these together with percutaneous techniques have been associated with a higher frequency of sural nerve injuries compared to open surgery (Čretnik et al., 2005). After surgery, same algorithm as non-surgical treatment is used, including a cast for 2 weeks followed by a walker brace with wedges (or walker brace instead of a cast) and supervised physiotherapy 2 weeks after the surgery.

REHABILITATION PHASES

The rehabilitation is often divided in four different phases depending both on the time from the injury/surgery but also on the functional status of the patient (Silbernagel et al., 2014). The four phases are Controlled mobilization phase (0-8 weeks), Early mobilization phase (6-11 weeks), Late mobilization phase (10-15 weeks) and Return to sport phase (3-12 months) (Silbernagel et al., 2014).

Each patient needs a tailored rehabilitation program with personal guidance aiming to return to their desired activity. Weaning off from the supportive walker brace can be a challenge for both the patient and the physical therapist. The risk for re-rupture is the greatest during this time period (Möller et al., 2001; Pajala et al., 2002; Rettig, Liotta et al., 2005) but there is also a need to load the tendon to promote the tendon healing and remodeling process. Since the load on the Achilles tendon is 2.5-3 times the body weight in each step during walking (Komi et al, 1992), the numbers of steps per day often needs to be limited during this phase to permit the tendon to adapt to the relatively small loads. Swelling and pain around the ankle are clinical signs of overuse. A compression stocking during daytime may be useful for minimizing swelling in lower leg (Rabe et al., 2018).

The return to physical activity & sport phase is often initiating around three to four months after the injury. During this phase, the patient needs guidance when to commence start with running and jumping activities in line with his or her goals.

It has been suggested that the following criteria can be used to decide when a patient is able to start with running activities (Silbernagel et al., 2014).

1. To be at least 12 weeks after injury and be able to perform 5 single-leg standing heel-rises at 90% of the maximum heel-rise height on the injured side.
2. If unable to achieve the above criteria by week 14-15, the patient can start running progression if they are able to lift at least 70% of their body weight during one single-leg heel-rise.

It is also suggested that there should be 3 days between running/jumping activities to allow recovery between sessions.

If the patient is aiming to return to racket sports, the rehabilitation should gradually include exercises to replicate the particular sports activity. Six to seven months after the injury, the patient should be able to bit by bit return to racket sports.

It is desirable that the coach and physiotherapist discuss the challenges and high impact movements in the particular racket sport. For example, in tennis, there are different techniques for the serve with different loading of lower limb, also the loading differs depending on which side is affected; the dominant or non-dominant side (Elliott, 2006). A relevant clinical question is if it is possible to practice step by step not losing technique with good quality?

PROGNOSIS

Do the individuals that suffers from an acute ATR recover adequately to return to their racket sport? In the Danish study from 1989 including 39 patients that suffered from an ATR during badminton, 46% resumed sport within 6 months of the injury. After 12 months 82% of the patients resumed activity. These results are in line with a meta-analysis by Zellers et al. that concluded that four out of five patient that suffered from an acute ATR returned to sport within 6 months (Zellers et al., 2016).

EARLY REHABILITATION PHASE (6-11 WEEKS) Visit for physical therapy 2-3 times a week and home exercises daily	
Exercise programme:	- Leg presses
- Exercise bike	- Leg extensions
- Ankle range of motion	- Leg curls
- Ankle strengthening using a resistance band or cable machine	- Foot exercises
- Sitting heel-rise with external load (25-50% of body weight)	**If the patient meets the criteria of five single leg heel-rises at 90% of height, then start:**
- Standing heel-rise progressing from two legs to one leg	- Bilateral rebounding heel-rises
- Gait training	- Bilateral hops in place
- Balance exercises	- Gentle jogging in place

Figure 4. A general rehabilitation programme during the early rehabilitation phase ad modum Silbernagel et al (Silbernagel et al., 2014).

However, it has been proven that an important factor to minimize ankle- and knee biomechanical deficits during more demanding activities after an ATR, is to regain the heel-rise height in the injured ankle within the first year after the injury (Brorsson, Grävare Silbernage et al., 2018). Moreover, seven years after an ATR, the patients still have deficits in heel-rise height, strength and endurance in the injured lower limb even if they have returned to middle-high physical activity (Brorsson, Willy et al., 2017). Heel-rise height has been shown to improve during the first two years after the injury but after two years no improvements in lower leg function has been found (Brorsson, Grävare Silbernage et al., 2018).

CONCLUSIONS

ATR is a common injury among racket sport players. If the injury is being recognized early and the patient receives individualized treatment, in combination with monitored physiotherapy during rehabilitation, players are likely to return to the same level of sports activity whether surgical or non-surgical treatment is chosen.

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Kinematics differences between a one-handed and a two-handed tennis backhand using gyroscopes. An exploratory study

Diferencias cinemáticas entre el revés a una y dos manos de tenis usando giróscopos. Un estudio exploratorio

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Abstract

The main objective of this article is to compare angular kinematics and intersegmental coordination of the upper limbs between one-handed and two handed backhands in a sample of 20 male competition players by using gyroscopes and compare ball speeds and accuracy obtained in both types of backhands. The angular kinematics, intersegmental coordination, ball speed and accuracy were compared during a specific stroke performance test using four inertial sensors (trunk, head, arm and forearm). We hypothesize that there will be significant differences in terms of ω_{peak} and intersegmental coordination in some of the segments measured between DH and SH by using gyroscopes, but the opposite will happen in the variables speed ball and accuracy. There are no significant differences between one-handed backhand and two-handed backhand in terms of speed and accuracy. Higher peaks angular speeds were found in the trunk and arm over the x axis in two-handed backhand which could indicate that this type of backhand generates greater trunk rotation and external rotation of the arm and forearm compared to one-handed backhand. The peak angular speeds were greater in the arm and forearm on the z axis in the case of one-handed backhand which is related to a greater extension of the forearm accompanied by a higher termination in the technical gesture. In conclusion, the proposed model of biomechanical analysis through the use of gyroscopes is especially useful for kinematic analysis of tennis strokes during field-based experimentation and could easily be adapted to other sports. It is also a low-cost and portable alternative that includes all instrumentation and data processing.

Keywords: *Wearable; inertial sensors; angular speed; upper body; racket sports.*

Resumen

El objetivo principal del presente estudio es comparar la cinemática angular y la coordinación intersegmentaria del tren superior entre el revés a una y dos manos de tenis en una muestra de 20 jugadores de nivel competición mediante el uso de giróscopos, y comparar las velocidades de pelota y la precisión obtenidas en ambos tipos de revés. La cinemática angular, la coordinación intersegmentaria, la velocidad de pelota y la precisión se obtuvieron de cada jugador mediante una prueba de golpeo realizada con cuatro sensores inerciales colocados (tronco, cabeza, brazo y antebrazo). Se sostiene la hipótesis de que se encontraran diferencias significativas en

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términos de ω_{pico} y coordinación intersegmentaria en alguno de los segmentos intervinientes en el revés a una y dos manos, pero sucederá lo contrario en las variables velocidad de pelota y precisión. Tras el análisis de los resultados, no se encontraron diferencias significativas entre el revés a una y dos manos en velocidad de pelota y precisión. Sin embargo, se encontraron velocidades angulares pico significativamente más altas en el tronco y brazo sobre el eje x en el revés a dos manos, lo que podría indicar que este tipo de revés genera una rotación de tronco y una rotación externa de brazo y antebrazo mayores que las del revés a una mano. Las velocidades angulares pico fueron significativamente mayores en el brazo y antebrazo sobre el eje z en el caso del revés a una mano, lo cual está relacionado con una mayor extensión del antebrazo acompañada de una terminación más alta del gesto técnico. En conclusión, el modelo propuesto de análisis biomecánico a través del uso de giróscopos es especialmente útil para el análisis cinemático de los golpes de tenis en estudios de campo y podría adaptarse fácilmente a otros deportes, suponiendo una alternativa portable y de bajo coste que además incluye toda la instrumentación y procesamiento de los datos.

Palabras clave: *Vestible; sensores inerciales; velocidad angular; tren superior; deportes de raqueta.*

INTRODUCTION

Physical fitness, motivation and tactical dexterity are important aspects to get a good performance in tennis, but the mechanical efficiency of the players´ strokes often determines the level of success both recreationally and competitively (Roetert et al, 1992). Although the forehand, compared to the backhand, allows for generating more speed which has an effect on the ball and it's accuracy after impact, this is also a basic groundstroke and is becoming increasingly important in modern tennis (Delgado-García et al., 2019; Fernandez-Fernandez et al., 2010; Reid, 2001). A player´s decision to use two-handed backhand (DH) or one-handed backhand (SH) is a key point in the tennis learning process, since the player will be able to obtain a major or minor biomechanical efficiency in this stroke depending on his decision (Genevois et al., 2015). For example, DH is the type of backhand that most of the baseline players usually choose, while the versatile players seem more likely to choose SH because it is easier for them making net approach strokes and backhands volleys (Genevois et al., 2015). Young tennis players prefer DH during their initiation phase since it requires less force than SH (Giangarra et al., 1993). Another factor that favors the selection of DH over SH in adult beginner players is that SH is more susceptible to tennis elbow (Giangarra et al., 1993; Roetert et al., 1995; Blackwell & Cole, 1994).

There is a need to carry out research that analyses the kinematics of the backhand since it is less studied than forehand or serve (Genevois et al., 2015; Bahamonde, 2005). The backhand is one of the two basic groundstrokes in tennis and the evolution of the backhand represents one of the biggest changes in tennis over the past decades (Genevois et al., 2015). The segments used for performing both backhands (DH and SH) are the same: hips, shoulder, upper arm and hand/racket rotation (Reid & Elliott, 2002). However, 3D photogrammetry research indicates biomechanical differences between DH and SH (Genevois et al., 2015; Giangarra et al., 1993; Akutagawa & Kojima, 2005). These studies show a sequential coordination between the different segments involved in performing the two backhands (Allen et al., 2016). It has been shown that intersegmentary coordination (IC) occurs from proximal to distal in terms of angular velocity and linear velocity (Marshall & Elliot, 2000) and that the moment of maximum trunk rotation acquires a fundamental character in the performance that we can achieve in this stroke (Genevois et al., 2015).

The biomechanical parameters of tennis strokes have been widely studied in laboratory conditions, but there is a shortage of studies that do it on the court (Allen et al., 2016). Only some biomechanical studies make of use inertial sensors in tennis (Cosac & Ionescu, 2015; Sharma et al, 2017), however after reviewing the literature, in most cases the devices are placed on the racket or forearm, and tennis performance is the result of sequenced whole body coordination (Allen et al., 2016). It will be vital also to analyze the trunk, arms and head to have a more complete monitoring of the kinematics of the stroke (Bertolotti et al., 2015).

Previous studies have shown that inertial measurement unit (IMU) gyroscopes are a valid alternative to 3D optical motion capture system for angular kinematics analysis in tennis (Delgado-García et al., 2021) since they allow capturing the rotational movements in the three axes of space; record the peak angular speeds (ω_{peak}) of the different segments and differentiating between different levels of play (Ahmadi et al., 2010). They also allow to discriminate the different phases of the strokes (Hansen et al., 2017; Büthe et al., 2016) and obtain the sequencing of the segments that are part of the kinematics of the stroke (Büthe et al., 2016).

The main objective of this article is to compare angular kinematics and intersegmental coordination of the upper limbs between two-handed and one-hand backhands in a sample of competition players by using gyroscopes. Additionally this study compares ball speeds and accuracy obtained in both types of backhand. We hypothesise that there will be significant differences in terms of ω_{peak} and intersegmental coordination in some of the segments measured between DH and SH by using gyroscopes, but the opposite will happen in the variables speed ball and accuracy.

METHOD

Sample

A sample of 20 male advanced players with a minimum of 15 years of experience (all of them were taking part in regional competitions) was used, 10 with DH and 10 with SH. The age range of the sample was 17 to 49 (29.55 ± 8.16) years. The anthropometric characteristics of the participants were obtained using the Inbody 230 bioimpedancemeter (Inbody Seoul, Korea). The average height of the sample was 177.33 cm ± 5.5 (means ± standard deviation), mass 79.3 kg ± 12.66, body mass index 25.9 ± 3.94, body fat mass 15.76 kg ± 9.34 and skeletal muscle mass 35.22 kg ± 4.48. Participants were instructed to have fasted in the previous two hours and not to have performed strenuous physical exercise in the 48 hours prior to the study. Sample exclusion criteria were musculoskeletal injury and the use of medications that could cause problems during the test. After receiving detailed information on the objectives and procedures of the study, each subject signed an informed consent form in order to participate, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2013). It was made clear that the participants were free to leave the study if they saw fit. The study was approved by the Institutional Review Board.

Procedures

Specific stroke performance test

The test was performed on an indoor court with type A surface (International Tennis Federation [ITF], 2015). Each player used their own racket, which was previously checked to ensure that it was in good condition according to the criteria of the International Tennis Federation (International Tennis Federation [ITF], 2015). Since the tension of the racket strings affects the control and the power of the stroke (Brody & Roetert, 2004) it was measured with a tensiometer (Tourna stringmeter, EE.UU). The tensions of the rackets were in a range of 19 to 25 kilograms. Sixty new and well-pressurized tennis balls (Wilson Trainer) with weight and size characteristics were used within the standards allowed by the ITF (2015). The tennis ball machine (Lobster Gram Slam 4, Lobster Sport Inc. North Hollywood, CA. EE.UU) it was calibrated before the start of each test following the manufacturer's instructions. Before starting the test, participants performed a standardized 8-min warm-up divided into general warm-up (mobility exercises) and specific that it consisted of a 5-min rally with a high-level player (it was the same for all participants). The subjects were given a heart rate monitor with the aim of controlling heart rate and thus preventing fatigue from being a contaminating factor during the development of the protocol. The next stroke series was not started until the subject reached a difference maximum of 10 bpm regarding the pulsations measured just after warm-up (Lyons et al., 2013).

After the warm-up, the protocol was explained to the subjects. The stroke protocol is based on previous study of Lyons et al. (2013). A total of 600 backhands were recorded (300 DH and 300 SH). To ensure that the time between strokes was constant in all subjects and in all series the resultant angular speed (R_ω) of the forearm sensor was used, taking the moment of appearance of the peaks (each peak was considered an impact), following a similar process from a previous study to detect falls (Bourke & Lyons, 2008). The total average time between strokes was 3.42 ± 0.025 seconds. The test consisted of three stroke series (alternating forehand and backhand) with 20 strokes each. The participants always had to hit parallel trying to send the ball to the different objectives of the opposite court (figure 1). The players were asked to "achieve the objectives with the greatest possible speed", similar indication to that made in previous studies of stroke accuracy (Landlinger et al., 2010; Van den Tillaar & Ettema, 2006). The Stalker Pro II speed radar (Stalker Radar, Plano, Texas) was placed in the center of the track and was oriented parallel to the lateral lines with the intention of minimizing the error due to the angle of the trajectory of the ball (Kelley et al., 2010). The ball bounce was recorded at 60 Hz with a rear and aerial viewpoint using the Panasonic HC-V160EC-K camera (Panasonic, Japan) with the aim of obtaining the accuracy achieved by each player. The accuracy of each shot was evaluated according to the area of the court where the ball had bounced (Figure 1). The balls that bounced off these targets were scored with zero. The total accuracy was calculated as the percentage of points obtained in relation to the total points possible.

Analysis of the gyroscope signal

A peak analysis of the gyroscope signal (Nexgen Ergonomic, Montreal, Canada) was performed in order to find both the magnitude and the timing of maximum rotation (rad s^{-1}) of different segments during each stroke. Five sensors (Nexgen Ergonomic, Montreal, Canada) were placed on the trunk, head, arm, and dominant forearm. This sensor location follows the guidelines of previous works (Ahmadi et al., 2010; Grimpampi et al., 2016; Ahmadi et al., 2009). The locations and axes of each sensor is shown in Figure 2. They were used at a sampling frequency of 128 Hz and record synchronously between each other. According to the manufacturers x and y axis gyroscopes has a range of ± 2000 deg s^{-1} and a typical noise density of 0.81 mrad/s/ $\sqrt{hz}$ and the z axis has a range of 1500 deg s^{-1} and a typical noise density of 2.2 mrad/s/ $\sqrt{hz}$.

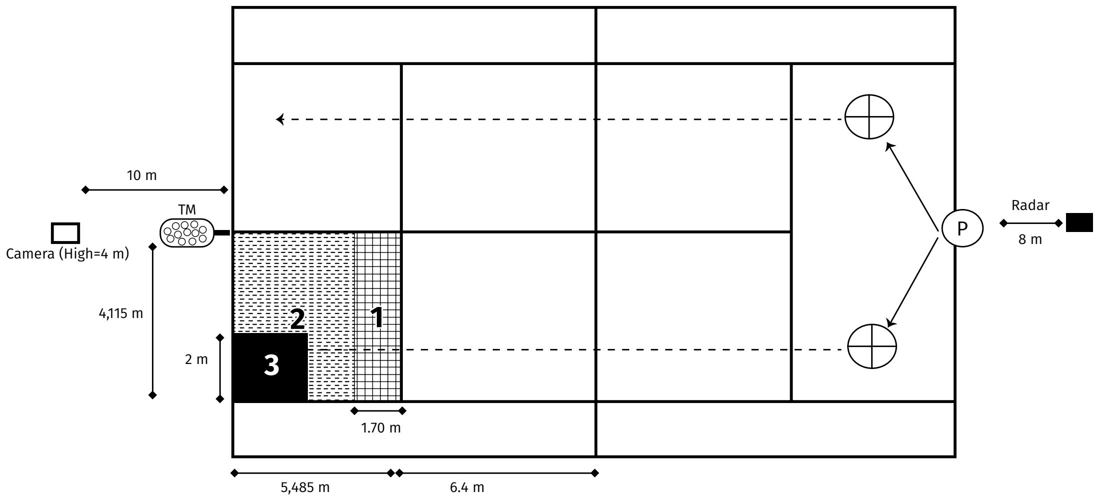

Figure 1. Stroke test with the dimensions and scores of the targets. The targets for the bottom shots are represented by the values 1, 2 and 3. The numbering of each zone corresponds to the score awarded to the participant. TM: Tennis ball machine.

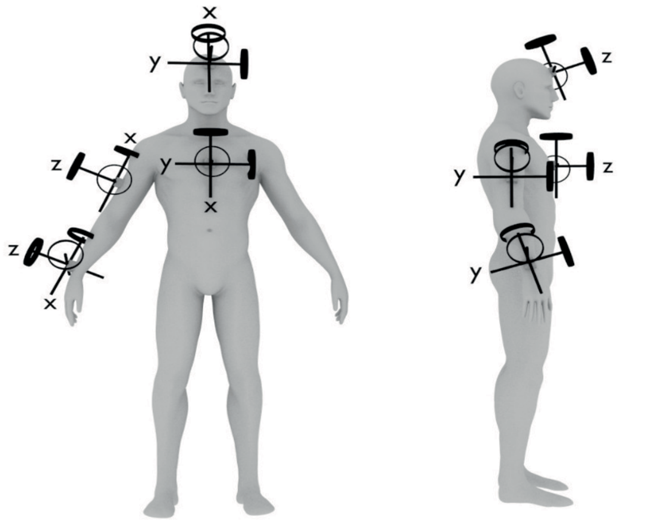

Figure 2. Positioning of the sensors and rotation axes. The circles represent the plane of rotation. The rotations on the x axis correspond to the turns on the longitudinal axis of the segment.

To verify the validity of the inertial sensors, an internal validation study was carried out with five subjects of different levels. The gyroscope signal was compared with a 3D photogrammetric analysis system (OptiTrack, Natural Point Corvallis, USA) and analyzed with Visual 3D (c-Motion, Inc., Rockville, MD, USA). The gyroscopes were placed in the same locations that in the stroke test described previously and each subject executed 5 series (2 series of forehands, 2 series of backhands and 1 series of serves) of 20 strokes each series hitting a ball fixed in an elastic bar (laboratory conditions). The signals of angular velocity in each of its axis (x, y and z) acquired with both systems (sensors gyroscopes and markers-based gyroscopes) was compared. For this, 300 correlations were made in which the average r was 0.985 ± 0.018 in forehand and backhand situations with and without the ball.

Angular Kinematic

The original unfiltered gyroscope signal was used so as to not modify the height of ω_{peak}. A semi-automatic peak search was carried out using the Origin 9 software (OriginLab Northampton, MA), with the function of the software "peak analysis". It was visually verified that the peaks were correctly selected with the TK Motion Studio software (APDM Inc, Portland, OR, USA), which allows us to capture the synchronized signal with a GoPro video camera (GoPro Inc., San Mateo, CA) set at 60 Hz, so that strange peaks can be identified and discarded. This analysis aimed to find both the magnitude and the timing of maximum rotation (rad/s) of the different segments during each stroke of the series. Taking into account the duration of a stroke and in order to avoid false positives, only those ω_{peak} that were found at ± 25 samples of the moment of appearance of the resulting peak of angular speed of the forearm ($R_{\omega peak}$ of the forearm). Other authors have also used the ω_{peak} to determine events (Bourke & Lyons, 2008).

Intersegmental coordination

A comparison of the Intersegmental coordination (IC) was made between ω_{peak} of the forearm (reference sensor) and ω_{peak} of the trunk, ω_{peak} of the head and ω_{peak} of the arm, for DH and SH. IC is related to the sequence of movements of the aforementioned segments. Other authors, like Grimpampi et al. (2016) have used the moment when the segment begins to rotate (angular velocity changes sign and increases or decreases significantly). However, in the present work it has been preferred to select the ω_{peak}, since in such explosive gestures as tennis strokes the moment of rotation start is more difficult to detect because the signal changes sign at several points on the x axis. In the case of trunk and arm, ω_{peak} were selected on the x axis (which corresponds to the longitudinal axis of these segments), where it is expected greatest angular speed will be found (due to the moment of inertia with a lower rotation radius).

In the case of the head, the resultant was selected ($R_{\omega peak}$ of the head), since it is more complex to determine the axis of rotation on which the maximum angular velocity occurs (the neck joint allows more degrees of freedom). The unit of IC is the number of samples. This unit can be transformed into time by dividing it by the sampling frequency of the sensors (128 Hz). Finally, IC was calculated by subtracting the moment of appearance of the ω_{peak} of the segment in question (trunk, head and arm) at $R_{\omega peak}$ of the forearm. $R_{\omega peak}$ of the forearm was considered the closest point to the impact of the ball. Bourke & Lyons (2008) also used R_{ω} but in a sensor placed on the trunk. In our study, a positive value in R_{ω} indicates that the peak appears after the moment of impact and vice versa.

STATISTIC ANALYSIS

Descriptive statistics are represented as mean and standard deviation. Tests of normal distribution and homogeneity, determined by the Kolmogorov Smirnov and Levene's test, respectively, were conducted on all data before analysis. The accuracy of each participant was presented as the percentage of points achieved with respect to the total (90 points) and the speed as the average speed of all their hits. Unpaired comparisons of means (t-test) were conducted between data from the two types of backhands for the variables stroke speed (km/h) and accuracy (%). The magnitude of the differences between values was also interpreted using the Cohen's d effect size (ES) (between-group differences (Cohen, 1988). Effect sizes are reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) (Cohen, 1988). In contrast, the ω_{peak} and IC of the different segments analysed did not follow a normal distribution. Therefore, a Mann-Whitney-Wilcoxon independent means comparison test was performed. The level of significance used was p<0.05. All statistical analyses were performed using the Origin 9 software program (OriginLab Northampton, MA), except the effect sizes that were calculated with the Psychometric freeware (Lenhard & Lenhard, 2016).

RESULTS

In table 1 we can see a comparison of the average speeds generated to the ball and the accuracy (%) of both types of backhands (SH and DH). Where despite the fact that the DH values are slightly higher for both average ball speed and accuracy, no significant differences were found between them (P> 0.005).

Table 1.
Comparison of average ball speed and accuracy between DH and SH of all participants.

Players **(SH)**	Ball speed *	Accuracy %	Players **(DH)**	Ball speed *	Accuracy %
1	103.2	61	1	90.8	32
2	104.4	33	2	103.2	58
3	89.6	37	3	96.9	35
4	103.9	46	4	87.9	43
5	96	52	5	76.9	31
6	82.5	52	6	82.5	45
7	94.3	43	7	82.8	36
8	92.3	40	8	87.5	60
9	81.1	34	9	92.3	36
10	98.9	42	10	90.1	43
Total	89.09 ± 7.52 *	42 ± 0.1 *	**Total**	94.62 ± 8.41*	44 ± 0.08*

* Means ± standard deviation; * Average ball speed

Figure 3 shows the comparison of the mean of ω_{peak} between DH and SH. Significantly higher ω_{peak} (rad / s) were obtained for the DH on the x axis of the sensors placed on the trunk and arm, and on the y axis of the sensor placed on the forearm. The effect size was large in the three cases (> 0.8). In the case of SH, ω_{peak} higher were obtained on the z axis of the sensors placed on the forearm and arm. Being in the case of the arm a moderate effect size (0.5-0.79) and in the forearm a large effect size.

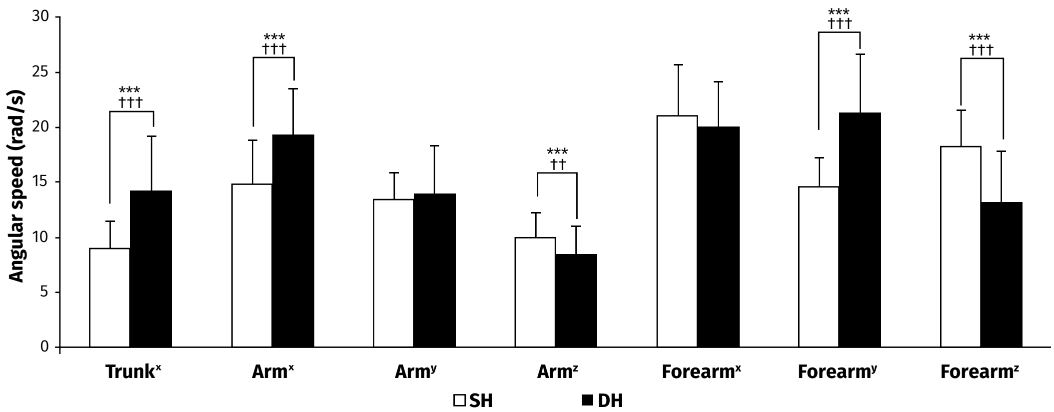

Figure 3. Comparison of the average of ω_{peak} between the two types of backhands on the different segments analysed (SH and DH). * p <0.025; ** p <0.01; *** p <0.001; * † small effect size; †† medium effect and ††† large effect.

Figure 4 represents the IC in relation to the temporal differences in the appearance of the ω_{peak} of the analysed segments, taking as reference $R\omega_{peak}$ of the sensor placed in the forearm, between DH and SH. Significant differences were found in the appearance of the ω_{peak} of the sensors placed on the arm and head between DH and SH. The effect size was small in both cases (0.2-0.4). There were no significant differences in the appearance of the ω_{peak} between DH and SH in the sensor placed in the trunk.

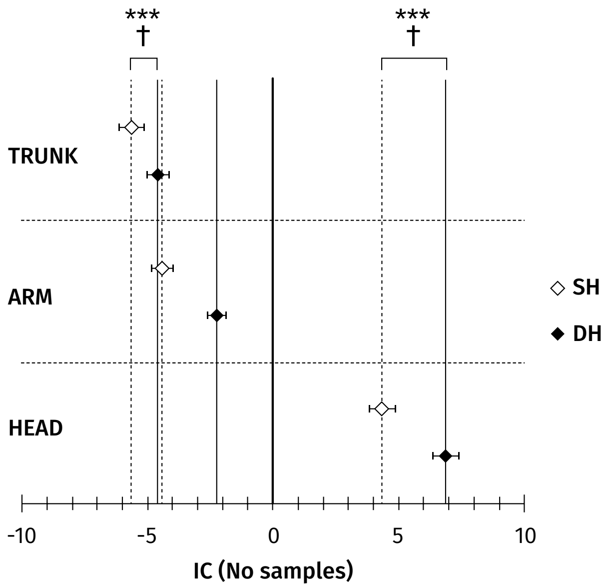

Figure 4. Comparison of the IC in the appearance of ω_{peak} in analysed segments taking as reference $R\omega_{peak}$ of the sensor placed in the forearm, between the DH and SH. Black rhombuses correspond to DH and white rhombuses with SH. * p <0.025; ** p <0.01; *** p <0.001; † small effect size (Fernandez-Fernandez et al., 2010).

DISCUSSION

Ball speed and accuracy

The average ball speed in SH was 89.09 ± 7.52 km/h while that in DH was 94.62 ± 8.41 km/h, although it is slightly higher in the DH no significant differences were found between them. Previous studies found that there are no differences in the ability to generate ball speed between DH and SH (Fanchiang et al., 2013). Regarding the accuracy obtained in the stroke performance test, no significant differences were found between DH and SH (42% vs 44%), which corroborates the results of previous studies (Muhamad et al., 2011; Stępień et al., 2011), which also did not find differences in accuracy comparing DH and SH. Both our results and of the literature consulted suggest that racket speed, ball speed and the accuracy of the stroke should not be affected by the type of backhand used; other factors such as kineanthropometry, coordination skill or player style will determine these variables (Reid & Elliott, 2002). Thus, our hypothesis is fulfilled since there are no significant differences in terms of ball speed and accuracy between DH and SH.

Angular Kinematic

In the present study biomechanical differences have been obtained in the ω_{peak} between DH and SH through the use of gyroscopes, which coincides with the results of the previous studies (Genevois et al., 2015; Giangarra et al., 1993; Reid & Elliott, 2002; Knudson & Blackwell, 1997; Choppin et al., 2011) in which similar differences were detected comparing both types of backhands by using 3D photogrammetry. Significantly larger ω_{peak} were obtained in the sensors placed on the trunk and arm on the x axis (rotational movements on the longitudinal axis) for DH, it is consistent with previous studies of Genovois et al. (2015) and Lo & Hsieh (2016) since both studies conclude that this type of backhand generates greater trunk rotation and external rotation of the arm and forearm compared to SH. They were also found ω_{peak} significantly larger for the sensor placed in the forearm on the y axis in the DH, but after reviewing the literature we have not found references that justify the finding. Instead, they were found greater ω_{peak} in the SH in the sensors placed on the arm and forearm on the z axis, which conforms to the results of Knudson & Blackwell (1997), Stępień et al (2011) and Reid & Elliot (2002) who detected a greater extension of the forearm accompanied by a higher termination in the technical gesture of the SH compared to the DH in a sample of competitive tennis players. In order to talk about anatomical movements based on ω_{peak} (captured with inertial sensors) in the different axes, we have to rely on the results of Choppin et al. (2011) that indicate that the angle between the face of the racket and the vertical is from 14 to 33 degrees. Taking into account the anatomy of the wrist, if the player will use an east grip or a little more closed such angle would make the forearm practically perpendicular to the ground, so that the y axis sensor would be parallel to the vertical and therefore a greater movement in z axis will indicate that the trajectory of the racket follows a path with greater vertical component (Kwon et al., 2017).

Intersegmental coordination

The comparison of the IC of the ω_{peak} between both types of backhand showed that both meet a sequential coordination between the different segments involved in the realization of the stroke (Allen et al., 2016). In addition, as in the study by Marshall and Elliott (2000) such sequential coordination occurs from proximal to distal in terms of angular speed and linear velocity for both, SH and DH. The point of maximum trunk rotation in the DH is significantly closer to the moment of maximum rotation of the forearm than in the SH, which could indicate that the hip begins to rotate earlier during two-handed backhand. The biomechanical differences found between DH and SH in terms of ω_{peak} and intersegmental coordination in some of the segments measured using gyroscopes confirm our initial hypothesis.

Head stabilization

In other sports where precision is an important factor, inertial sensors have been used to study the movements of the head (Fogt & Persson, 2017) but there are not many scientific studies about the movements of the head during a tennis stroke (Reid et al., 2013). Yet, gaze direction is a subject of great interest for tennis coaches (Lafont, 2008). In our study, there were significant differences in the moment of appearance of the ω_{peak} of the head. It is difficult to discuss these results since the movement of the neck depends to some extent on the movement of the trunk (*this needs to be further studied*). This ω_{peak} of the head during the impact could affect the movement control and the accuracy of the stroke, as can be deduced from the conclusions of the study by Lafont (2008), who revealed that elite players show a characteristic head fixation in the direction of the contact zone at impact and during the follow-through. It is not clear if this head fixation is more related to maintaining a stable head and body position during skill execution or to the need to extract operational information from the ball (Lafont, 2008).

LIMITATIONS

Five-marker model has been the most used with 3D photogrammetric systems to analyse biomechanical differences between DH and SH (Reid, 2001; Bahamonde, 2005; Reid & Elliott, 2002). In contrast, in our study with inertial sensors, four sensors have been used since the legs sensors were suppressed in order to capture only the kinematics differences of the upper body (Ahmadi et al., 2010). The results of the present study should be interpreted with caution because of possible errors when performing analysis of human movements (Akutagawa & Kojima, 2005). Placed instruments may also contain a source of error due to skin movement (Manal et al., 2003). Another limitation of the study was the number of participants used and their play level (intermediate). In future studies, the sample will be significantly increased and only competitive tennis players will be measured. In addition, it might be interesting for future studies to determine the maximum speed without to obtain a reference value. It could be that and athlete increases their accuracy at the expense of speed.

CONCLUSIONS

The proposed model of biomechanical analysis with gyroscopes is especially useful for the kinematic of tennis strokes during field-based experimentation and could easily be adapted to other hit sports with and without implements. It is also a low-cost and portable alternative that includes all instrumentation and data processing respect to others motion capture systems. Our hypothesis is fulfilled in the light of the results of the study. There are no significant differences between one-handed backhand and two-handed backhand in terms of speed and accuracy. Although it has been shown that there are significant biomechanical differences between two backhands, higher peak angular speeds were found in the trunk and arm over the x axis in two-handed backhand, which could indicate that this type of backhand generates greater trunk rotation and external rotation of the arm and forearm compared to SH. The peak angular speeds were greater in the arm and forearm on the z axis in the case of one-handed backhand which is related to a greater extension of the forearm accompanied by a higher termination in the technical gesture. Both types of backhands followed a sequential coordination from proximal to distal, but in the two-handed backhand the moment of maximum trunk rotation was located significantly closer to the point of maximum rotation of the forearm compared with one-handed backhand.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Management of Tennis elbow in racket sports – a literature review

Tratamiento de codo de tenista en deportes de raqueta – revisión de la literatura

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Abstract

Background: Pain from the lateral aspect of the elbow is a common symptom in racket sports, both in recreational and competitive players. In Tennis elbow (TE), the pain is elicited from the lateral epicondyle and the common extensor origin just distal of the epicondyle. The symptoms are aggravated by gripping activity and might be related to activity level, in work as well as in recreational or elite racket sports. TE is considered to be an overuse injury of degenerative nature and the diagnose is easily made, based on a typical history and clinical findings. **Objective:** To present current knowledge concerning management of TE in racket sports by a review of the literature. **Methods:** Narrative literature review. **Results:** An overview of TE in racket sports with highlight on the clinical features, alternative diagnoses and suggested treatments in the literature. Since TE is considered to be an overuse injury, the paper also provides advises for training plan besides management until resolution of symptoms. Conclusions: This painful condition is self-limiting with a good prognosis. No treatment has convincingly evidence, besides methods for reducing pain symptoms. When the pain symptoms are under control, it is important that the return to racket sports is gradual.

Keywords: *Tendinopathy, racket sport, overuse injury, lateral epicondylitis.*

Resumen

Antecedentes: El dolor en la parte lateral del codo es un síntoma común en los deportes de raqueta, tanto en jugadores recreacionales como de competición. En el codo de tenista (CT), el dolor se produce en el epicóndilo lateral y en el origen del extensor común justo distal al epicóndilo. Los síntomas se agravan con actividades de agarre y pueden estar relacionados con el nivel de actividad, ya sea en el trabajo o en los deportes de raqueta recreacionales o de élite. Se considera que el CT es una lesión por sobreuso de naturaleza degenerativa y el diagnóstico se realiza fácilmente basado en la historia y los hallazgos clínicos. **Objetivo:** Presentar el conocimiento actual sobre el tratamiento del CT en los deportes de raqueta a través de una revisión de la literatura. Métodos: Revisión de la literatura narrativa. **Resultados:** Un resumen del CT en los deportes de raqueta con énfasis en las características clínicas, los diagnósticos alternativos y los tratamientos sugeridos en la literatura. Dado que el CT se considera una lesión por sobreuso, el artículo también hace sugerencias para un plan de entrenamiento adicional al tratamiento hasta que se resuelvan los síntomas. **Conclusiones:** Esta condición dolorosa es autolimitada y tiene un buen pronóstico. No hay tratamiento con evidencia determinante, además de los métodos para reducir los síntomas de dolor. Cuando los síntomas de dolor están bajo control, es importante que el regreso a los deportes de raqueta sea gradual

Palabras clave: *Tendinopatía, deporte de raqueta, lesión por sobreuso, epicondilitis lateral.*

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INTRODUCTION

Pain from the lateral aspect of the elbow is a common symptom in racket sports, both in recreational and competitive players. In badminton 2.4%-13% of all injuries have been reported to be elbow injuries (Caine et al., 2010), and the prevalence of elbow injuries in tennis is 1.3%-14.1% with no difference between men and women (Abrams et al., 2012). Tennis elbow (TE) has been reported to be the most common injury among recreational paddle-tennis players (Castillo-Lozano & Casuso-Holgado 2017). There are few data on elbow injuries in squash, a study on professional squash players showed that only about 1% of all injuries were elbow injuries (Horsley, O'Donnell, & Leeder, 2020). The incidence of TE in a general population is described to be approximately 2%, and the diagnosis is mostly seen between 40 and 53 years of age (Sanders et al., 2015). Tennis players appear to be affected even at younger age; 16-36 years (Maffulli et al., 1990).

There are a variety of proposed diagnoses; lateral elbow pain, lateral epicondylalgia, lateral epicondylitis, lateral epicondylosis, extensor tendinopathy etc. TE is probably the most common used diagnosis and includes localized pain from the common origin of the wrist extensor muscles at the lateral epicondyle, with pain during repetitive gripping activities such as in playing tennis or other racket sports. Triggering factors for pain symptoms are change of equipment, technique or higher intensity in activity (Walker-Bone et al., 2012).

The background for the name of the "Tennis elbow" condition was that it was seen in tennis players with single hand backhand stroke already in the 19th century, where the flexors of the dominant hand stands for all power to hold on the grip to the racket and stabilize the wrist during the strike, when the ball is met and redirected back to the opponent (Hume et al., 2006; King et al., 2012). In tennis the wrist is used to stabilize, not for active dorsal flection. However, in other racket sports, such as badminton and paddle-tennis, static and dynamic extension of the wrist might also lead to the same pathophysiology, that is also seen in manual computer working environment. The symptoms can be aggravated when there is a pronation of the hand; the supinator muscles can also be involved (Lawrence et al., 1995).

The pathogenesis is not known, but TE is considered to be an overuse injury of degenerative nature (Kraushaar & Nirschl, 1999). Biopsies from patients in a chronic stage, i.e. after three months duration of pain symptoms, taken from the origin of extensor carpi radialis brevis, have shown degenerative changes with disorganized collagen, invasion of fibroblasts and vascular hyperplasia without any signs of inflammation (Nirschl, 1992). The pain mechanism is not fully understood, but biopsies have shown presence of neurotransmitters that imply a kind of "neurogenic inflammation", which should be distinguished from traditional prostaglandin mediated inflammation (Zeisig et al., 2009).

CLINICAL FEATURES

When an athlete has pain from the lateral aspect of the elbow, triggered during racket sport, TE should be considered (Shiri & Viikari-Juntura 2011). The onset is often insidious, but can be more acute after temporary overload (Smidt & van der Windt 2006). The pain is evoked while gripping the racket and there might be a loss of grip strength. Often there is a complaint of stiffness of the elbow, especially in the morning, or after having the elbow fixed in the same position, and the pain is most often related to activity level (Shiri & Viikari-Juntura 2011). The tendinopathy is located in the common extensor origin, located just distally of the top of the lateral epicondyle, where the most tender spot is found during palpation (Villaseñor-Ovies et al, 2012). Pain is provoked from the same area by resisted extension of the wrist and occasionally resisted extension of the third finger. Test for grip strength is painful and the strength might be reduced (De Smedt et al., 2007).

The diagnosis is verified by physical examination and further investigation is not necessary with a typical history and clinical findings. If the diagnosis is unclear, the method of choice is examination with ultrasound and Doppler (Zeisig et al., 2006). In cases of TE, there are typical findings with hypoechogenic areas in the common extensor origin with high blood flow seen on Doppler examination (Obradov & Anderson, 2012). Examination with ultrasound or magnetic resonance imaging (MRI) cannot be used to evaluate effect of treatment, since the pathological findings may be seen despite clinical improvement (Chourasia et al., 2013). Notable is, that if there has been a local intervention, there is no possibility to distinguish eventual underlying pathology from changes after injections, surgery etc.

Racket sport requires experience from training and puts high demands on correct technique, otherwise pain from hand, wrist, shoulder, abdomen and back, besides from the elbow, might also be experienced.

In cases with TE without any response to treatment after a couple of months, the diagnosis must be re-evaluated, and differential diagnosis considered. Neck and shoulder symptoms must be requested for and the cervical spine must be examined looking for referred pain. (Berglund et al., 2008). If the clinical diagnosis is TE, but the effect of treatment is absent, there might also be a coexistent radial tunnel syndrome. The diagnosis for the latter is tenderness over the radial tunnel and positive test for the radial nerve (Naam & Nemani, 2012). Elbow pain can also arise from the lateral collateral ligament that is closely related to the common extensor origin and might give the same symptoms as TE after a sprain with or without instability (Clarke et al., 2010). Local synovitis on the undersurface of the common extensor origin can give the same symptoms as TE (Lattermann et al., 2010).

Figure 1.
The condition was observed already in the 19th century. The term “Tennis elbow” was introduced in 1882; the condition was seen in tennis players with single hand backhand strokes, where the flexors of the dominant hand stand for all power to hold on the grip to the racket and stabilize the wrist during the strike, when the ball is met and redirected back to the opponent.

More generalized synovitis or arthritis of the radio-humeral joint can be suspected if there is a painful and restricted range of motion (Ravalli et al., 2019). Another intra-articular pathology that can be considered is osteochondritis, especially in younger individuals, where MRI will give the correct diagnosis (Kotnis et al., 2012).

TREATMENT

TE has been shown to be a self-limiting condition with a good prognosis. Most cases are fully recovered in eight to twelve months regardless treatment, but some cases are recalcitrant (Bisset et al., 2006; Zeisig, 2012; Kim et al., 2021). The golden standard for management is correction of training, related to the specific demands of the racket sport, and different kinds of physiotherapy, as described below. No other regimen has convincingly evidence for a faster recovery, even though there are, of course, different methods for reducing pain symptoms (Struijs et al., 2001; Brosseau et al., 2002; Buchbinder et al., 2005; Taylor & Hannafin, 2012; Coombes et al., 2013; Hoogvliet et al., 2013). First of all, the training schedule, technique and equipment must be overlooked. Core and shoulder stability must be included in physical examination. Ergonomics is important, not only during sports, since gripping activities is a part of daily life (Shiri & Viikari-Juntura 2011). See Table 1.

Methods for reducing pain symptom can be used, even though there is lack of evidence in the literature for methods being superior to other treatments, including alternative activity (“rest”), painkiller, stretching, muscle strengthening (eccentric training), manipulation, electrotherapeutic modalities and acupuncture (Bateman et al., 2021b; Kim et al., 2021).

The forces during the strike with the racket can be transferred from the common extensor origin and might be reduced using epicondylitic bandage, taping or orthosis stabilizing the wrist (Kroslak et al., 2019).

Table 1.
Brief advices on management of lateral elbow tendinopathy.

- keep in mind; self-limiting condition with good prognosis
- adjust training plan and amount of training/competition
- correction of technique
- look for core and shoulder stability
- correction of equipment
- rehabilitation training
- physical therapy with individualized pain management
- don’t forget differential diagnoses

Injection therapies are tried with cortisone, prolotheraphy, platelet rich plasma, autologous blood, sclerosing agent, botulinum toxin and glycosaminoglycan (Placzek et al., 2007; Franchini et al., 2018; Lenoir et al., 2019), but there is no solid evidence for injection therapies to be superior to physical therapy.

Surgery has been proposed to be an alternative treatment in smaller studies. However, it cannot be recommended due to risk of complications. Also, there are other better alternatives for management (Solheim et al., 2013).

In summary, there is no golden standard for treatment for TE. In a search (Medline and Cochrane database) for treatment for TE published 2017-2021, there was 46 meta-analysis and systematic reviews published. Even though these publications are based on randomized controlled trials (RCTs), there were no strong evidence for any treatment. The only significance found was for injections with saline (placebo) (Table 2). This implies that TE is a self-limiting condition in weeks to months, but sometimes up to years, and “wait and see” is an alternative to intervention (Bisset et al., 2006).

PRACTICAL PERSPECTIVES

TE is an overuse injury that is common in racket sports. The background is not fully known, but training load, technique and equipment seem to be important factors for the development of TE. The condition is self-limiting, with a good prognosis (Bisset et al., 2011).

In tennis and badminton, TE is well known by players, trainers and medical staff. Since paddletennis is a relatively new racket sport that has gained a lot of interest, it might attract players without previous experience of the loading of racket sports and gripping activity as holding on to a racket. Therefore, a new injury pattern, including a possible high frequency of elbow pain, could be expected in the future (Castillo-Lozano & Casuso-Holgado, 2017). This is an important field for further research.

Table 2.
Forty-six meta-analysis and systematic reviews of treatment for tennis elbow were published 2017-2021. There is only one treatment that showed significance; saline injection (placebo).

Number of studies	Treatment	Conclusion summary
Injection therapy		
14	Platelet-rich plasma (PRP)	No support for PRP, corticosteroids improves outcome short time, PRP effective in long time
3	Autologous blood, bone marrow, dry needling	No significance, week evidence, low effect
2	Botulinum toxin	Temporary effect, heterogenity
2	Saline injection (Placebo)	Significant improvement, improvements
Non operative treatment		
6	Shock wave	No significance, more randomized controlled trials (RCTs) needed, no clinical effect
2	Acupuncture	Low evidence, more RCTs needed
5	Physiotherapy	Can improve, low effect, better than injection
2	Tape	Effective during rehabilitation
3	Orthosis	Low quality evidence
Surgical treatment		
7	Surgery, arthroscopy	No significance, low quality evidence, may be clinical difference

TE is a self-limiting condition with a good prognosis. However, it is important to find ways to help and support the individual athlete in reducing malalignments and provoking factors, as well as pain management in order to maintain physical activity and performance. Many different methods have been suggested. There is, so far, no golden standard for interventions, so every individual case should be carefully assessed by trainers concerning correction of training and equipment. Shoulder stability and core are also not to be overlooked.

Professional correction of this kind might, of course, be a problem for recreational racket players without trainers, especially in relatively new and growing sports with a lot of new players without racket experience, which for example is the case in paddle-tennis in some countries. Also, the correct way to perform strokes differ between racket sports. Stroke technique in one racket sport may not be optimal when a player changes to another racket sport.

Rehabilitation training and physical therapy of different kinds could be tried, with the perspective that "one size doesn´t fit all". This means that methods for pain management, as described above, can differ considerably between different players (Bateman et al., 2021b). A good strategy is: "Hold on to your physical therapy, and hold on to your racket!"

Different invasive interventions, such as injections and surgery have been suggested (Dines et al., 2015), however, there is no strong evidence for any of these methods. Also, invasive interventions might have irreversible side-effects, and might also reduce the possibility to distinguish eventual underlying pathology in clinical follow up of the conditions with ultrasound or MRI (Savnik et al., 2004).

Injection therapies, especially corticosteroid injections, have been used since decades (Claessen et al., 2016). But is it working on tendinopathies? Without signs of inflammation? It has also been shown complications such as atrophy of the overlying tissues (fat) (Coombes et al., 2010). Surgery is often described as effective in recalcitrant cases, where "everything else" has been tried. This gives no alternative method to use in a RCT, and there is always a risk for complication as infections, aggravated pain symptoms, scar and skin adhesion or lost grip strength (Buchbinder et al., 2011). There is also a lack of evidence for return to racket sport after surgery.

LIMITATIONS OF THE REVIEW

Injury reports from the literature show a large variation in design, methodology and injury definitions, which makes it difficult to estimate exactly how common the condition is in different racket sports. It is also possible that players have symptoms, but are still playing, which has been seen in other overuse pain conditions in racket sports (Caine, 2010). Therefore, it is even more difficult to estimate the prevalence as well as the incidence of TE.

Also, the different studies also have different inclusion criteria and outcome measures, that makes evaluation of different treatment i.e. symptom-reducing intervention methods, difficult to compare. Future studies must be recommended to have a standard for injuries and inclusion criteria, as well as standardized treatment and rehabilitation methods, to make it possible to perform meta-analysis to evaluate effects of interventions (Bateman et al., 2021a).

A recent consensus statement by a working group from the International Olympic Committee has suggested definitions of injuries and illnesses in sports (Bahr et al., 2020). A similar work on badminton injuries has been done by a medical expert group in the Badminton World Federation (Gijon-Nogueron et al., 2022). The results from these studies will be a valuable contribution to standardized future studies.

CONCLUSIONS

Pain from the lateral aspect of the elbow are common symptoms in racket sports. The underlying pathology might be tendinopathy in the common extensor origin at the lateral epicondyle – TE – and is considered as an overuse condition. The diagnosis is based on a history of overuse activities and typical findings during physical examination. TE is most often self-limiting with good prognosis, but pain symptoms might need attention. No treatment has showed convincingly evidence being superior to others, all are different methods for reducing pain symptoms. Like in other overuse conditions, individual adjustment of technique and equipment (i.e. grip width, stiffness of racquet stringing, shock absorption of the racket), as well as gradual loading of racket sport is recommended.

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Original Investigation

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The influence of self-reported total sleep time and sleep quality on physical performance in junior tennis players

La influencia del tiempo de sueño total autorreportado y la calidad del sueño en el desempeño físico de jugadores júnior de tenis

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Abstract

Studies have shown the importance of sleep on tennis skill execution; however, its influence on physical performance metrics is unclear. This study aimed to examine the extent to which sleep duration and sleep quality metrics influence physical performance metrics in junior tennis players. Thirty-six junior tennis players from Australia and Germany completed the Consensus Sleep Diary over seven nights. A novel total sleep score based on current National Sleep Foundation recommendations was generated (calculated as the percentage of the average standardised sleep metrics), for each player. Players physical performance was measured using a comprehensive tennis-specific testing battery. This included sit and reach test for flexibility, counter movement jump and overhead medicine ball throw for power, 5-, 10- and 20-metre sprints for speed, tennis agility test for agility and reaction time, grip strength for strength, repeat sprint ability for anaerobic capacity and the Hit and Turn Tennis Test for aerobic capacity. Teenage (14 to 17 years of age) players reported significantly lower sleep duration (471 ± 116 min versus 543 ± 72 min; $p < 0.001$, $d = 0.83$) and sleep efficiency (90% ± 11% versus 94 % ± 5%; $p = 0.011$, $d = 0.49$) metrics than school-aged players. Players with higher self-reported sleep quality had slower reaction times during a tennis agility test ($r = 0.604$, $p = 0.011$). However, players who reported feeling more rested and refreshed had faster reaction times during a tennis agility test ($r = -0.579$, $p = 0.020$). No other significant associations were present between self-reported sleep metrics and physical performance metrics. Nevertheless, feeling well-rested and refreshed, one of the primary outcomes of sleep, improves reaction time during a tennis-specific agility test. However, physical performance metrics are not significantly influenced by small variations in recommended sleep duration and sleep quality ranges.

Keywords: *Reaction time; Restfulness, Sleep efficiency; Teenager; Tennis agility.*

Resumen

Diversos estudios demuestran la importancia del sueño en la ejecución de las habilidades en el tenis, sin embargo, su influencia en las métricas del desempeño físico no es clara. El objetivo de este estudio es analizar hasta qué punto las métricas de la duración y calidad del sueño influencian las métricas del desempeño físico en jugadores júnior de tenis. Treinta y seis jugadores júnior de tenis de Australia y Alemania completaron el Diario de Sueño Consensuado durante siete noches. Para cada jugador se creó una nueva puntuación del sueño total basada en las recomendaciones actuales de la Fundación Nacional del Sueño (calculada como el porcentaje de la media

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de las métricas de sueño estandarizadas). El desempeño físico de los jugadores fue medido con una batería integral de pruebas específicas para el tenis. Las pruebas incluidas fueron la prueba de sentarse y alcanzar para flexibilidad, el salto en contramovimiento y el lanzamiento de balón medicinal sobre la cabeza para la potencia, sprints de 5, 10 y 20 metros para la velocidad, la prueba de agilidad en tenis para la agilidad y el tiempo de reacción, fuerza de agarre para la fuerza, capacidad de repetir sprint para la capacidad anaeróbica y la prueba de golpear y girar en tenis para la capacidad aeróbica. Los jugadores adolescentes (de 14 a 17 años) reportaron métricas significativamente menores en la duración del sueño (471 ± 116 min frente a 543 ± 72 min; p <0,001, d = 0,83) y la eficiencia del sueño (90% ± 11% versus 94 % ± 5%; p = 0,011, d = 0,49) comparadas con las de jugadores en edad escolar. Los jugadores con mayor calidad de sueño autorreportada tuvieron tiempos de reacción más lentos durante la prueba de agilidad en tenis (r = 0,604, p = 0,011). Sin embargo, los jugadores que reportaron sentirse más descansados y renovados tuvieron tiempos de reacción más rápidos durante la prueba de agilidad en tenis (r = -0,579, p = 0,020). No se encontraron otras asociaciones significativas entre las métricas de sueño autorreportadas y las del desempeño físico. No obstante, sentirse descansado y renovado, uno de los resultados principales del sueño, mejora el tiempo de reacción en la prueba de agilidad específica para tenis. Por otra parte, las métricas del desempeño físico no están influenciadas significativamente por las pequeñas variaciones en la duración del sueño y los rangos de calidad del sueño recomendados.

Palabras clave: *Tiempo de reacción, descanso, eficiencia del sueño, adolescente, agilidad en tenis.*

INTRODUCTION

Current recommendations, by the National Sleep Foundation (NSF), suggest that school-aged children (6-13 years of age) and adolescents (14-17 years of age) should achieve 9-11 hours and 8-10 hours of sleep each night, respectively (Hirshkowitz et al., 2015). Junior (<18 years of age) athletes often receive less sleep than these recommendations (Riederer, 2020). Sleep quality has also been shown to be impaired in junior athletes (Suppiah et al., 2021). Sleep duration and sleep quality may be impaired by lifestyle factors, including school commencement times, homework, and potential social media and gaming (Hansen et al., 2017; Wahlstrom et al., 2017). Additionally, junior athletes' sporting commitments may impact their sleep opportunity, thus reducing their sleep duration and sleep quality (Dumortier et al., 2018; Kölling et al., 2016).

Studies in young adult tennis players have found that partial sleep deprivation (reduced sleep duration) negatively impacts serve, forehand and backhand accuracy (Reyner & Horne, 2013; Vitale et al., 2021). One week of sleep extension to nine hours per day has been shown to increase serve accuracy in college tennis players (Schwartz & Simon, 2015). These studies indicate a positive link between sleep duration and execution of tennis skills. However, increased sleep duration as part of a mixed-method recovery strategy (the use of multiple recovery strategies) did not positively impact tennis performance outcomes (Lever et al., 2021). Though, it did improve lower body power and reduce perceived muscle soreness in junior tennis players, indicating a link between increased sleep duration and improved physical performance (Duffield et al., 2014).

While there is a paucity of studies investigating the effects of sleep on physical performance in junior athletes (Riederer, 2020), numerous studies have been conducted in adult athletes from various sports, with equivocal findings (Watson, 2017). Specifically, reaction times have been shown to slow when partial (reduced sleep duration) or complete (maintain wakefulness) sleep deprivation occurs (Fullagar et al., 2015; Reilly & Edwards, 2007; Watson, 2017). Maximal strength appears to be unaffected by sleep duration (Reilly & Edwards, 2007; Sinnerton & Reilly, 1992; Watson, 2017). However, the effects of sleep duration on aerobic capacity and sprint performance are less clear, with some (Mah et al., 2011; Peacock et al., 2018; Watson, 2017), but not all (Reilly & Edwards, 2007; Sinnerton & Reilly, 1992), studies reporting decrements in performance following nights with reduced sleep duration.

Current studies have reported associations between physical factors and tennis performance (Fett et al., 2020; Ulbricht et al., 2016). Given these associations, aspiring junior tennis players must optimise their physical performance to ensure tennis success. Understanding the factors influencing physical performance, including sleep, is then of paramount importance. Therefore, we aimed to examine the extent to which sleep duration and sleep quality metrics influence physical performance metrics in Australian and German junior tennis players. We hypothesised that junior tennis players with sleep duration and sleep quality metrics that meet the NSF recommendations will have superior performance in physical tests.

METHODS

Players

Thirty-six junior tennis players volunteered for this study. Twenty-six were school-aged and 10 were considered teenagers. Players were recruited through local clubs and coaches in Perth, Australia and Cologne, Germany. Data presented in our study represent a subset from a more extensive study investigating predictors of performance in junior tennis players. Inclusion criteria for our study were as follows; be between 9 and 18 years of age, have a tennis ranking attained through competition, and currently perform at minimum one training session per week. All players and their guardians provided written informed consent before engaging in study testing procedures. Our study was approved by the Edith Cowan University Human Research Ethics Committee (ID: 00673).

Experimental Design

A cross-sectional study design was utilised to evaluate associations between sleep duration and sleep quality and physical performance outcomes in junior tennis players. Players' sleep duration and sleep quality were monitored for seven nights across weekdays and weekends, with a minimum of five nights needed for further analysis. Physical performance testing was conducted in one testing session on a tennis hard court surface; the testing sessions were conducted between 9:00 am and 5:00 pm and was administered by the same examiners. The experimental design and timings can be seen in Figure 1.

MEASURES

Sleep-wake behaviour

The Consensus Sleep Diary (CSD) measured players' sleep duration and sleep quality (Carney et al., 2012). This measure was developed by the Pittsburgh Assessment Conference in 2012 and has since been validated (Carney et al., 2012; Maich et al., 2018). When completing the diary, players were required to report the following information for each day/night: (i) what time did they go to bed (bedtime), (ii) what time they tried to sleep, (iii) how long it took them to fall asleep, (iv) how many times they woke during the night and for how long, (v) what time they woke for the day, and (vi) what time they got out of bed. Additionally, the CSD included 5-point Likert scales for players to rate their sleep quality and restfulness. The information derived by the CSD enables calculation of time in bed (TIB), sleep onset latency (SOL), wake after sleep onset (WASO), sleep duration, sleep efficiency (SE), sleep quality and restfulness. Sleep duration, SOL, WASO and SE, measured by the Consensus sleep diary, have been validated against actigraphy (Maich et al., 2018). The CSD can be seen in Figure S1 of the supplementary file.

Each player's total sleep score was calculated based on age-appropriate (school-aged: 9 to 13 years or teenager: 14 to 17 years) sleep duration and sleep quality (sleep latency, wake after sleep onset and sleep efficiency) recommendations from the NSF (Hirshkowitz et al., 2015; Ohayon et al., 2017). The recommended ranges for each sleep variable can be seen in Figure 2. A detailed description of how the total sleep score was determined can be seen in Figure S2. The total sleep scores, presented as a percentage, represent the level of adherence (no adherence 0% to complete adherence 100%) each player had to sleep duration and sleep quality recommendations outlined by the National Sleep Foundation (Hirshkowitz et al., 2015; Ohayon et al., 2017).

Physical and Mental Fatigue

The Chalder Fatigue Scale (CFS) evaluated fatigue, including physical and mental fatigue (Chalder et al., 1993). The CFS is an eleven-item validated questionnaire designed to indicate the current physical and mental fatigue. Scores are then totalled and range from 0-33, with higher scores indicating greater fatigue levels. A score of 22 indicates a player was feeling fatigued at the time of completion.

Anthropometrics

Standing heights were measured and recorded to the nearest centimetre (0.01 m) using a tape measure. Players stood tall with their back against a wall, the distance from the ground to the top of their heads recorded. Body mass was measured using a set of electronic scales and was recorded to the nearest gram (0.01 kg).

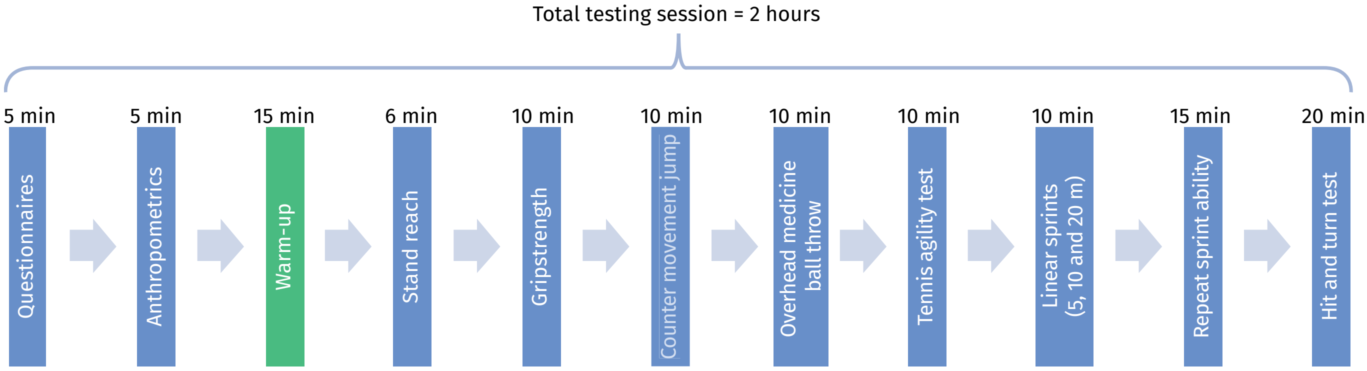

Figure 1. Experimental design, inclusive of order and timings of testing session.

Physical assessments

Flexibility

Flexibility was measured using a Sit and Reach test; players are required to sit on the ground with their legs extended and the soles of their feet against a sit and reach box (Flex tester, Novel Products Incorporated, Rockton, USA). Players had their hands on top of one another with palms facing down and reached forward as far as possible without their knees bending, holding this position for 2-3 seconds (Roetert et al., 1992). Players performed three trials, one after the other, with the best trial achieved recorded and analysed.

Linear speed

Linear speed was assessed over 5, 10 and 20-metre distances using timing light sensors (Speed light, Swift Performance, Queensland, Australia). The testing procedure was previously used with junior tennis players; it involves players beginning their linear sprint from a standing start, positioned 50 centimetres behind the first timing light sensor (Ulbricht et al., 2016). Players were allowed practice runs if required after the initial instructions were provided. Each player then performed two maximal 20-metre sprints with a two-minute passive recovery between sprints. Sprint times over 5-, 10- and 20-metre distances were recorded to the nearest millisecond (0.01 sec).

Tennis Agility Test

Agility was assessed using the Tennis Agility Test (TAT), which required players to start in a standing 'ready position', straddling the centre mark of the baseline. The tester initiated the test who performed a forehand or backhand swing, indicating that the player runs to their right or left, respectively. The player was required to run to the doubles sideline, perform a forehand or backswing, then run to the opposing doubles sideline, perform a forehand or backhand swing before running back to the centre mark to complete the test. The players were provided with a clear explanation of the test and allowed a practice run before three trials, interspersed with two-minute passive recovery periods. The three trials' best reaction time (the time between tester and player movements) and total time (time to complete the test) were included for analysis. Both times were recorded to the nearest 0.3 milliseconds (0.03 sec) using Kinovea (open-access video analysis software; https://www.kinovea.org).

Counter movement jump

Players jump height during a counter movement jump (CMJ) was used to determine lower body power. To reduce the involvement of arm-swing during the jump, players held a pole across their shoulders (Legg et al., 2017). A linear positional transducer (GymAware, Kinetic Performance Technology, Canberra, Australia) attached to the end of the pole was used to measure the jump height of players. Players were instructed to jump as high as possible whilst keeping the pole level; the trial was repeated if the player tilted the pole. Three maximal CMJs were performed with two-minute passive recovery periods between jumps. The maximal height of each jump was recorded to the nearest centimetre (0.01 m).

Overhead medicine ball throw

The upper body power of players was assessed using an overhead medicine ball throw; this test has previously been used with junior tennis players (Ulbricht et al., 2016). This test requires players to stand with their feet side by side and, using both hands, throw a two-kilogram medicine ball overhead as far as possible. Players were instructed not to step forward when throwing as the measurement was taken from their feet to the point where the ball landed; if a player stepped forward, the throw was retaken. A total of three throws were performed, with a two-minute passive recovery period between throws. The furthest horizontal distance from the thrower to the landing position of the medicine ball was recorded and used for analysis. All throws were recorded to the nearest five centimetres (0.05 m).

Grip strength

Upper body strength was assessed using a grip strength test, commonly used to measure strength in junior tennis players (Fett et al., 2020; Girard & Millet, 2009; Ulbricht et al., 2016). A hand dynamometer (Advanced Hand Dynamometer, TTM, Japan) was gripped by the player and positioned by the side of their body; it was then squeezed maximally for three seconds. The player's grip strength was measured in kilograms (kg), and the best of two trials on each hand, separated by two minutes of passive recovery, was used for further analysis.

Repeat Sprint Ability

The anaerobic capacity of players was assessed using the repeat sprint ability test; this test has recently been performed with junior tennis players (Vitale et al., 2021). The test required players to sprint 20 metres as fast as possible every 20 seconds for ten repetitions. The sprint times of players were measured using timing gates (Speed light, Swift Performance, Queensland, Australia) placed one metre above ground level. The anaerobic capacity was determined by the fatigue decrement score, calculated using the following formula (Chapman & Sheppard, 2011; Vitale et al., 2021).

Fatigue decrement (%) = ((total sprint time – ideal time) / total sprint time) x 100

Hit and Turn Tennis Test

The aerobic capacity of players was assessed using a tennis-specific endurance test called the Hit and Turn Tennis Test; this test is reliable and valid (Ferrauti et al., 2011). The test was delivered by a standardised audio file that dictates the direction and speed players move. Players were required to run and sidestep in the indicated direction and perform forehand and backhand swings until they could not make the time or voluntarily withdrew.

Statistical analysis

As determined by the Shapiro-Wilk test, data were normally distributed and presented as mean ± standard deviation (range). A T-test was conducted to identify if the sleep latency, wake after sleep onset, sleep duration or sleep efficiency differed between school-aged children and teenagers. General linear modelling was also used to determine the influence of sleep duration and sleep quality on each of the physical performance metrics. All models were adjusted for sex, age and nationality. False discovery rate (FDR) correction was applied to account for multiple models and to mitigate false positive results. The effect sizes were reported as Cohen's *d* or *r* (partial correlations). Cohen's *d* thresholds were identified as small = 0.2, medium = 0.5 and large = 0.8 (Cohen, 2013). While Cohen's *r* thresholds were identified as small = 0.1, medium = 0.3 and large = 0.5 (Cohen, 2013). Analysis was conducted using R Studio software package, Version 1.1 (RStudio Team, 2020). A p-value <0.05 was considered statistically significant.

Overall, there were 36 players in our study, n=22 players from Australia and n=14 players from Germany. Of these players, 25 were male, and 26 were categorised as school-aged (9 to 13 years). Demographic information for players is presented in Table 1.

Table 1.
Brief advices on management of lateral elbow tendinopathy.

	M ± SD	Range
Age (years)	12 ± 2	(9, 17)
Tennis experience (years)	6 ± 2	(1, 11)
Hours played per week	8 ± 4	(1, 17)
Height (centimetres)	162.1 ± 11.1	(139, 179.5)
Body mass (kilogram)	50.0 ± 11.6	(29.8, 81.5)

Note. M, Mean; SD, standard deviation.

Consensus Sleep Diary

Teenagers had 72 minutes (p <0.001, d = 0.83) less sleep duration than school-aged children for each night across the seven nights. Additionally, Teenagers had a 4% (p = 0.011, d = 0.49) lower sleep efficiency than school-aged children each night across the seven nights (Figure 3).

Players average sleep quality score was 3 ± 1 (2, 5), which is indicative of 'fair' sleep quality. The average score for how well-rested or refreshed players felt was 3 ± 1 (1, 5), indicative of 'somewhat rested'. Players average total sleep score was 67% ± 9% (46%, 86%). The descriptive data for the physical performance metrics are presented in Table 2.

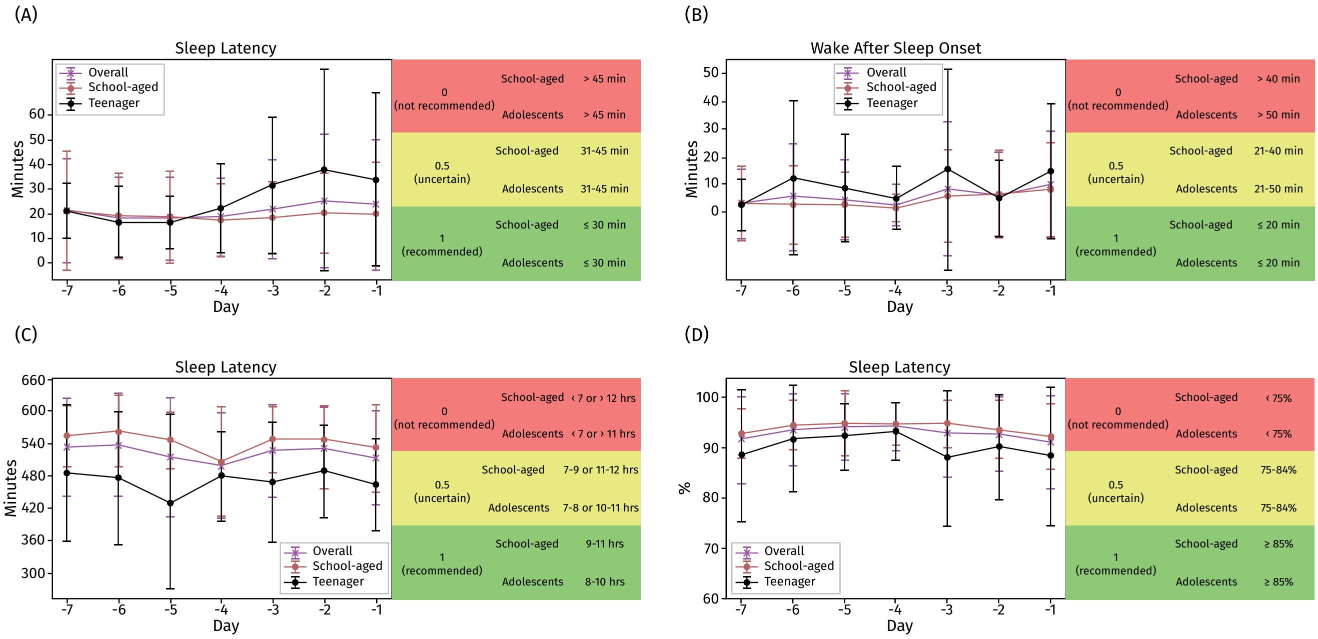

Figure 2. The mean and standard deviations of self-reported scores of the seven-day sleep diary for overall, school-aged and teenage players. The recommended ranges from the National Sleep Foundation for each age category are also provided for each sleep metric. Green indicates recommended, yellow indicates uncertain and red indicates not recommended. Sleep metrics include: Sleep latency (A), wake after sleep onset (B), sleep duration (C) and sleep efficiency (D).

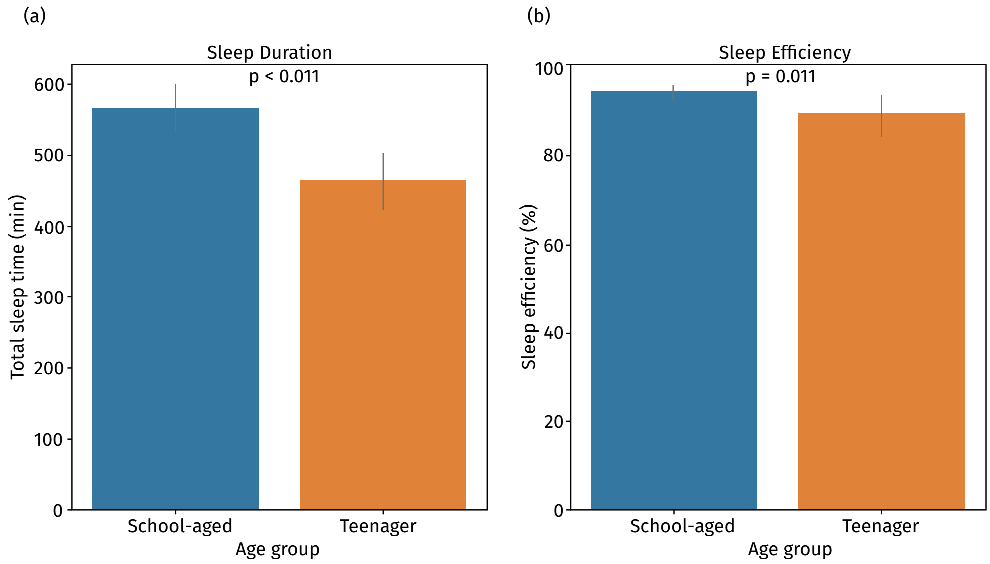

Figure 3. Bar plot of the mean sleep duration (a) and sleep efficiency (b) of school-aged and teenage players. Standard deviation for each group is indicated by the black error bars.

Table 2.
Physical performance tests presented as mean, standard deviation and range.

	Physical performance tests	
	M ± SD	Range
Chalder Fatigue Scale (#)	11 ± 3	(4, 21)
Sit and reach (#)	22 ± 11	(1, 50)
Counter movement jump (metres)	0.32 ± 0.06	(0.20, 0.49)
Overhead medicine ball throw (metres)	5.6 ± 1.3	(2.6, 8.5)
Sprints		
5 metres (seconds)	1.12 ± 0.21	(0.71, 1.51)
10 metres (seconds)	2.04 ± 0.23	(1.48, 2.60)
20 metres (seconds)	3.63 ± 0.35	(2.81, 4.55)
Tennis Agility Test		
Reaction time (seconds)	0.41 ± 0.14	(0.20, 0.80)
Total time (seconds)	6.83 ± 0.52	(6.13, 8.50)
Grip strength		
Dominant side (kilograms)	27.4 ± 9.8	(13.8, 48.0)
Non-dominant side (kilograms)	24.0 ± 8.7	(11.5, 44.0)
Repeat Sprint Ability (%)	6.34 ± 2.64	(1.63, 14.18)
Hit and Turn Tennis Test (#)	9.9 ± 4.1	(2.3, 18.0)

Note. M, Mean; SD, standard deviation.

Associations

Sleep and physical

Sleep duration did not significantly impact any physical performance tests. No significant impact was found between sleep quality metrics, including SOL, WASO, and SE, or the overall sleep score and any of the physical performance tests. Higher self-reported sleep quality scores (r = 0.604, p = 0.011) resulted in slower TAT reaction times. While higher self-reported restfulness scores (r = -0.579, p = 0.020) resulted in faster TAT reaction times (Figure 4).

DISCUSSION

The primary aim of this study was to explore associations between physical performance metrics and sleep duration and sleep quality in junior tennis players. The results from our study indicate that sleep quality, as measured by self-reported restfulness, had a significant positive impact on the reaction time of players undertaking the TAT. This finding aligns with previous literature showing the significant influence of sleep quality on athlete reaction times (Fullagar et al., 2015; Reilly & Edwards, 2007; Watson, 2017). Specifically, slower reaction times were reported after one night of partial sleep deprivation in athletes across various sports (Fullagar et al., 2015). Sleep deprivation is thought to negatively affect non-executive functions (automatic processes) utilised during reaction time tasks (Tucker et al., 2010). Thus, players who felt well-rested and refreshed, one of the primary outcomes of sleep, may have had improved automatic processes when reacting to the stimulus during the tennis-specific agility test.

Players who reported better subjective sleep quality were found to have slower TAT reaction times. This result contradicts the positive relationship observed between self-reported restfulness and reaction time from our study. This unexpected finding may be due to ceiling effects for our study's subjective sleep quality measure. In particular, the majority of players in our study scored above fair for subjective sleep quality (indicated in Figure 4); thus subjective sleep quality scores may not have been low enough to compromise reaction times. Further research is required to ascertain the self-reported sleep quality threshold needed to instigate a change in physical performance.

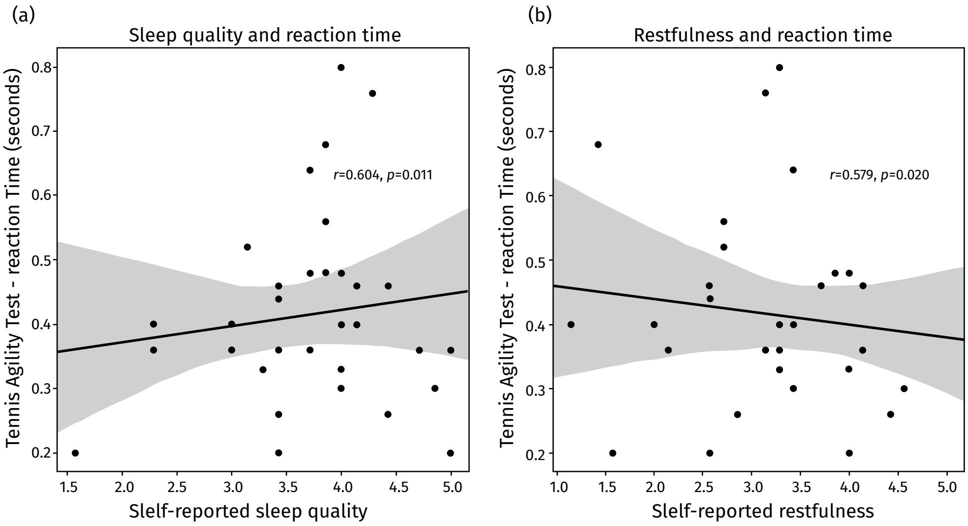

Figure 4. Scatterplots with regression model fit (black line) and 95% confidence intervals (shaded grey area) of the Tennis Agility Test reaction times and (A) self-reported sleep quality and (B) self-reported restfulness.

This study found that sleep duration and sleep quality were not significantly associated with repeat sprint ability. This result is in agreement with findings from Vitale et al. (2021), which reported no impact of sleep restriction on repeat sprint ability. Contrary to our expectations, our results revealed that sleep duration and sleep quality were not associated with aerobic performance (Hit and Turn Tennis Test). This finding was unexpected as reduced sleep duration has been linked with increased perceived exertion and declines in pre-exercise muscle glycogen stores, both essential for aerobic performance (Skein et al., 2011; Temesi et al., 2013; Watson, 2017). Further research using objective sleep measures is required to determine the effects of sleep duration and quality on aerobic performance in junior tennis players.

The findings of our study show no effect of sleep duration or sleep quality on speed, power and strength metrics. These findings align with previous literature where maximal speed, power, and strength have been found to not be negatively impacted by acute sleep deprivation (Blumert et al., 2007; Fullagar et al., 2015; Reilly & Edwards, 2007; Watson, 2017). Interestingly, sustained partial sleep deprivation of three hours' sleep per night over three nights has negatively impacted strength performance in weightlifting athletes (Reilly & Piercy, 1994), suggesting that performance decrements may only arise with sustained sleep deprivation. Sleep deprivation was not observed in the seven nights recorded (Figure 2), as all nights met the recommended sleep durations (Hirshkowitz et al., 2015). Therefore, further research is required to ascertain if partial sleep deprivation impacts physical performance in junior tennis players.

Potential limitations

This study did not control time of day when conducting performance testing, which may have impacted player performance. Testing was conducted during daylight hours between 9:00 am and 5:00 pm. Given that these were young amateur tennis players, we were required to comply with their schedules, including school, training, and family commitments thus representing a "real life" situation for coaches and players. The sample size calculation performed for this study indicated a required sample of 55 (α = 0.05, power = 0.80). Unfortunately, this study was only able to recruit 36 junior tennis players. While lower than the calculated sample size, the included sample is larger than previous studies undertaken in this area (Jarraya et al., 2014; Lever et al., 2021; Reyner & Horne, 2013; Vitale et al., 2021). Players' sleep duration and sleep quality were recorded subjectively using a sleep diary. This method is subject to memory bias as it relies on the recollection of players and cannot identify unconscious awakenings. It is, however, more ecologically valid than lab-based measures as it allows players to sleep in their natural environment and engage in their everyday routines. The benefit of this is we collected over 2,000 data points of sleep and had high participation due to the ease of use. Finally, sleep diaries were completed over weekdays and weekends, potentially biasing the data due to social commitments, such as school start times. However, all participants completed a sleep diary over weekdays and weekends to reduce any bias. This approach is also ecologically valid as it is reflective of data collection in the 'real life' setting, where such factors are not controlled.

Future research

While our study results indicate that physical performance is unaffected by sleep duration and sleep quality in junior tennis players, further studies using objective sleep monitoring are required. Furthermore, future studies should aim to control the time of day when testing occurs, as this has been shown to influence physical performance outcomes (Knowles et al., 2018). In addition to the testing time, future studies should also measure players chronotype to determine if the influence of sleep on physical performance differs for morning versus evening chronotypes. Finally, future studies should also aim to investigate the effects of sleep duration and sleep quality on tennis match performance as the decline in reaction time speed found in our study may have a large influence on tennis match outcomes.

CONCLUSION

Our study investigated the effects of sleep duration and sleep quality on physical performance metrics in junior tennis players for the first time. The main finding from our study was that if players felt more rested and refreshed, their reaction time during a tennis agility test was faster. Additionally, sleep duration and sleep quality had no significant impact on any physical performance variable, which may have been due to the recorded sleep duration and sleep quality metrics being within the recommended ranges (Hirshkowitz et al., 2015; Ohayon et al., 2017). Nevertheless, the findings from our study support the notion that physical performance metrics are not significantly influenced by small variations in sleep duration and sleep quality.

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Superior Gaze Strategies of Elite Badminton Players and the Significance of Natural Research Conditions

Estrategias de la mirada superiores en jugadores de bádminton de élite y la importancia de las condiciones naturales de investigación

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Abstract

Gaze behavior and performance of internationally ranked players and "near"-expert players were investigated under field conditions for the game situation service-return in badminton. According to literature, it was assumed that expert players focus more frequently on the racket arm, wrist, and racket of the opponent, while less experienced players focus on the shuttle. Thus, gaze strategy would have an influence on performance. The results contradicted the initial hypotheses: the higher the performance level of the athletes, the more frequently they directed their gaze to the shuttle. Non-professional players were found to focus more often on the upper body and face. To improve gaze behavior in the service situation, on-court drills with focusing on the shuttle region are assumed to be advantageous for athletes of all skill levels. Our research showed that players use other visual search strategies when observing a real opponent then when confronted with a two-dimensional stimulus.

Keywords: *Gaze behavior, racket sports, experts-near-experts, elite badminton .*

Resumen

La conducta de la mirada y el desempeño de jugadores de categoría internacional y "casi" expertos fueron investigados en condiciones de campo para la situación de juego servicio-devolución en bádminton. Según la literatura, se asumía que los jugadores expertos se enfocan con más frecuencia en el brazo de la raqueta, la muñeca y la raqueta del oponente, mientras que los jugadores menos experimentados se enfocan en el volante. Por tanto, la estrategia de la mirada tendría una influencia en el desempeño. Los resultados contradicen las hipótesis iniciales: entre más alto sea el nivel de desempeño de los atletas, más dirigen la mirada al volante. Los jugadores no profesionales se enfocaron más en la parte superior del cuerpo y el rostro. Se supone que los ejercicios en campo enfocados en el área del volante sirven para mejorar la conducta de la mirada en la situación de servicio en los atletas de todos los niveles de habilidad. Nuestra investigación demuestra que los jugadores usan unas estrategias de búsqueda visual al observar a un oponente real diferentes a las que usan con un estímulo de dos dimensiones.

Palabras clave: *Conducta de la mirada, deportes de raqueta, expertos-casi-expertos, bádminton de élite.*

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INTRODUCTION

In many sports, fast and efficient perception of various visual stimuli has high impact on the performance of an athlete (Hüttermann et al., 2018; Jendrusch, 2011; Jin et al., 2011). Especially in fast team and racket sports, the outstanding speed and ball velocities present a minimal time frame for the motor response of a player, e.g. the defense of a spike in volleyball or the action of the goal keeper in handball. In these game situations, successful motor reactions are hardly possible without an efficient perception and anticipation of the opponent´s actions, because the flight time of the moving object is shorter than the physiologically required time for information processing (Müller & Abernethy, 2012). In badminton, e. g., world class players generate shuttle velocities of more than 100 m/s (Gawin, Beyer, Büsch, & Høi, 2012). The defending player must begin his action before the shuttle trajectory is clearly visible. Otherwise, the remaining time is insufficient to perceive and process the information and to initiate the motor response to intercept the shuttle at the anticipated point of contact.

The importance of visual perception for performance in elite sports is highlighted in a quickly increasing scientific body (Klostermann & Moeinirad, 2020). Commonly, the characteristics of visual performance are studied by comparing the visual strategies of experts and non-experts (Hüttermann et al., 2018; Mann et al., 2007; Vickers & Adolphe, 1997). Aspects of superior perceptual-cognitive performance of expert performers are higher response accuracy, faster reaction time, and different gaze behavior (Gegenfurtner et al., 2011; Mann et al., 2007) and many studies have revealed significant performance differences between experts and non-experts for these aspects (e.g., Mann et al., 2007; Rienhoff et al., 2016; Vickers, 1996; 2016).

Regarding response accuracy, there is evidence that experts react more accurately than non-experts in specific game situations. For example, highly skilled badminton players are able to anticipate the trajectory or direction of a shuttle more precisely than less skilled players by "reading" the movement of the opponent at an early state of action (e. g., Abernethy & Russell, 1987a; Hagemann & Strauß, 2006). This superior perception is based on different utilization of relevant information from visual cues. Non-experts commonly observe the movement of the racket to anticipate the shuttle´s trajectory, whereas experts pick up information about the intended action at an early stage by recognizing the movements of the playing side arm (Abernethy & Russell, 1987b). This strategy enables them to calculate the appropriate response earlier and their prediction of the ball´s trajectory will more likely be correct.

Another performance factor is response time. Experts show significantly shorter response times - the time interval necessary for perception, information processing and the start of the motor response - than non-experts (Mann et al., 2007; Gegenfurtner et al., 2011). There is consistent evidence that highly skilled athletes terminate decision making earlier and, therefore, reach the required position, e. g. when defending a spike in volleyball or a penalty throw in handball "just in time" (Hossner et al., 2014; Lienhard et al., 2013; Schorer, 2006).

Highly skilled volleyball players finalized the decision for motor response at an earlier point of time and therefore more accurately than less skilled players, but commonly commenced the motor response later (Hossner et al., 2014; Lienhard et al., 2013). Research by Vickers and Adolphe (1997) revealed similar results. Expert volleyball players initiated the motor response at a later point of time when receiving a service than near-experts (Vickers & Adolphe, 1997). The less skilled players changed their position even before the server made contact with the ball, while the experts remained in the receiving position longer while tracking the oncoming ball.

Goalkeepers at a high performance level in handball also started their motor response later than non-experts (Schorer, 2006). This behavior enabled them to initiate the movement just in time, allowing them to execute the motor task successfully. Initiating movement too early would have allowed the opponent to change their strategy. According to Schorer (2006), this "just-in-time" reaction indicates an essential skill of high performing athletes in sports that afford a complex timing.

These observations are associated with motor tasks in which a player must reach a ball or the required position of the anticipated motor action just in time. However, demands differ in game situations in which athletes have to act as quickly as possible – as in many typical game situations in badminton. For example, the service return in the doubles disciplines requires starting the movement towards the shuttle as soon as possible (Gawin et al., 2013). Such game situations differ fundamentally from the just-in-time paradigm. The motor response must not only be started just in time, but immediately. There is also evidence that experts reach the required position faster than non-experts because of their superior anticipation (Mann et al., 2007).

Another aspect of gaze behavior concerns gaze strategies. The large number of studies in this field and the increasing heterogeneity of results caused Klostermann and Moeinirad (2020) to review the state in gaze behavior research in the recent decades. Considering at least 81 studies, they extracted four "main gaze variables" (Klostermann & Moeinirad, 2020, p. 153), number and duration of gaze fixations, location and duration of the final fixation (Quiet Eye, QE). Relatively consistent results have been published in the recent years for the last two variables – the gaze location and QE, for example, that expert athletes focus different visual cues when compared to less skilled performers and that they utilize longer final fixations.

The QE phenomenon seems to be consistent across many domains of sport. Mann et al., (2007) list publications about QE in various sports, such as rifle shooting, billiards, golf, volleyball, or basketball. For further information about the Quiet Eye theory, please see Gonzales (Gonzalez et al., 2015), Vickers (2016), Mann et al., (2007), or the review by Rienhoff, Tirp, Strauss, Baker and Schorer (2016).

The gaze location, an athlete focuses central-foveal, is assumed to contain task and decision-relevant information (Nakashima & Kumada, 2017). There is evidence that a specific gaze strategy is related to performance, and that there are differences between experts and non-experts (e. g., Gegenfurtner et al., 2011; Hubbard & Seng, 1954; Land & Tatler, 2001; Savelsbergh et al., 2002; Vickers, 2006; Vickers & Adolphe, 1997). Especially in interceptive sports, like net or racket games, superior gaze strategies are assumed to strongly influence performance. Perception, information processing, and initiating the motor response are all one process, which causes a minimal time frame and high time pressure. Therefore, many studies deal with the analysis of gaze behavior of athletes in racket or net sports, e. g. baseball, tennis, table tennis or badminton:

Long before mobile eye trackers were introduced, Hubbard and Seng (1954) analyzed the gaze behavior of professional baseball batters. They could show that the participants initially fixated the trajectory of the oncoming ball but then stopped the eye movement before hitting the ball at a region before the point of contact. This outcome was confirmed in a study involving volleyball by Vickers and Adolphe (1997). Highly skilled athletes in volleyball differ from less skilled athletes in their gaze strategies when receiving a service. Like the baseball players, the experts stopped their eye movement before the point of contact. Near-experts, in contrast, followed the trajectory of the ball more frequently until the ball made contact with the lower arms (Vickers & Adolphe, 1997).

Studies in the fields of tennis and table tennis focused on the question of how the ball was observed during and after the execution of the opponent´s action (e. g., Lafont, 2008; Ripoll & Fleurance, 1988; Rodrigues et al., 2002). Apparently, experienced table tennis players merely directed their gaze at the ball in the initial phase of the trajectory when receiving the ball laterally (Ripoll & Fleurance, 1988; Rodrigues et al., 2002). After that, the gaze was oriented towards a space that was located in front of the anticipated trajectory or at the region of ball contact (Ripoll & Fleurance, 1988). This result, again, was considered a confirmation of Hubbard and Seng's findings (1954), highlighting the conclusion that experts seem to be able to execute a successful stroke without constantly tracking the ball.

To analyze the service situation in badminton, Alder et al., (2014) combined the measurement of kinematic data and eye movements of elite and less skilled badminton players (Alder et al., 2014). The aim was to uncover the kinematic parameters that provide early information about the intention of the server. For this purpose, the serves of elite badminton players were videotaped and the kinematics were analyzed. These video scenes subsequently served as stimuli in a life-size temporal occlusion test while the gaze behavior of the receiving players was measured. Analyses revealed that professional badminton players more frequently directed their gaze to the racket and the racket wrist of the server than less skilled players, who tended to fixate the shuttle (Alder et al., 2014).

The service situation in elite badminton doubles has undergone in-depth analyses because this game situation has a profound impact on performance during competitions (Li, 2005; Liu & Zheng, 2009; Tian, 2004; Zhong & Xie, 2008). About one third of all points in doubles matches are initiated or made in the service situation comprising at least service, return, and second return (Gawin, Beyer, Büsch, & Hasse, 2012). Basically, the server has the choice between two tactical options – a low short service and a so-called flick serve to the rear court (figure 3). The returning player should anticipate the intention of the server and execute his movement towards the shuttle as quickly as possible to hit the shuttle in a superior position for an offensive return. Top players need about 300 milliseconds to reach the shuttle after a short serve, and it has been found that successful elite male players make contact with the shuttle significantly faster when returning the service (Gawin et al., 2013).

Many of the studies above, especially those dealing with gaze behavior in badminton (Abernethy & Russell, 1987a, 1987b; Alder et al., 2014), were conducted using two-dimensional video sequences as stimulus material. However, according to Shim and colleagues (Shim et al., 2005) and Mann et al., (2007), there is evidence that using two-dimensional video footage as stimulus affects the outcome of the analysis of real-world tasks. It is likely that participants show different visual search behavior when faced with real opponents in their natural environment. Moreover, the review article by Hüttermann and colleagues (2018) summarizes that 69 % of the eye tracking studies considered were carried out in the lab. In the majority of these studies, athletes had to react to stimuli on a video screen. Even some research under field conditions, e. g. Alder and colleagues (2014), did not use real opponents but rather man-sized video screens on the court. These experimental conditions are likely to bias the outcome of these studies and the transfer to the natural environment to develop practical implications (Hüttermann et al., 2018). Therefore, since stimuli are presented in a laboratory setting and lack one dimension, one might challenge the assumption of addressing the specificity of the experts' skills. The same applies to the required motor responses presented in many studies.

Meanwhile, it is possible to measure the gaze behavior of players under real-world conditions using mobile eye-trackers, and it can be supposed that measurements on court with real opponents will lead to divergent results compared to applying only video-based stimuli.

In the first step, the objective of this study is to reveal efficient gaze strategies of athletes in relevant game situations by identifying the strategies of elite performers (players competing at an international level) in comparison to players of an intermediate level of play. In a second step, the influence of the gaze strategies on situation-specific performance in elite badminton players will be analyzed to develop practical implications.

Therefore, the gaze behavior of elite badminton players and intermediate club level players in the game situation service return was investigated in the first part of the current study. In the second part, the motor performance of the elite players was measured, and the correlation between their gaze strategies and their performance during the service return was analyzed. According to the studies in racket sports listed above, it was hypothesized that…

1) …elite badminton players are more likely to focus on peripheral segments of the opponent, such as the playing side arm, the racket, and wrist, when preparing for their motor response, while less-skilled players focus more frequently on the shuttle, and

2) …that the gaze strategies of elite players are related to their specific performance in the rally opening situation.

METHODS

Sample

Badminton players of diverse skill levels were recruited for the current study. The sample was divided into elite badminton players (professionals) and intermediate club level players (non-professionals). The intermediate players group consisted of 13 experienced players (3 female, 10 male, age 31.5 ± 10.4) who competed in the regional league system. They all were badminton players at an intermediate level of play and were chosen because of their highest possible performance level of club players in the nearby region.

For the elite group, 22 nationally and internationally ranked (14 female, 8 male, age 23.2 ± 4.9) members of the German national team, German junior national team, or national teams of other nations were recruited for this study. This recruitment comprised all healthy national team players, who participated at a training intervention at the German national training center in Mülheim an der Ruhr at the time of this study. The elite group was subdivided into two subgroups: six olympic athletes (“A-National”, 4 female, 2 male, age 29.0 ± 3.6) and 16 further members of the German national team who compete internationally but not at an Olympic level (“B-National”, 9 female, 7 male, age 20.9 ± 3.0).). This subdivision was based on the assumption that different performance groups of elite level would display further differences in gaze behavior. All athletes were informed about the aims and risks of the study in advance by the coaches and the authors and gave their consent to participate in the study.

Instruments

The gaze behavior of the players was recorded using a mobile eye tracker by SMI (ETG2). The highest sampling rate of the infrared cameras in the eye tracking glasses that capture the eye movements is 60 Hz in combination with a front camera that records the eye view of the participant at 30 Hz. In the present study, the sampling rates of the front and the eye recording cameras were synchronized, and therefore the gaze behavior was measured at a frequency of 30 Hz. This caused a time interval of 33.3 milliseconds between frames. The algorithm to discriminate fixations from saccades is based on a threshold that is integrated into the eye tracker software. This threshold is either an angle velocity of more than 100° /s or a combination of angle velocity (8° /s) and skewness. Basically, when the recorded eye movement exceeds these thresholds, the eye event is classified as a saccade. According to Hessels and colleagues (Hessels et al., 2018), this method of eye event detection meets the computational method of defining fixations and saccades. Therefore, in this study, fixations and saccades were differentiated by the in-built algorithm of the eye tracker. For the discussion about the importance of a clear definition of eye movements, see the review by Hessels et al., (2018).

The athletes’ kinematics were analyzed using the high-speed camera system Marathon Ultra by GS Vitec (Bad Soden, Germany). Two synchronized cameras with a sampling rate of 500 Hz (at 1200 x 800 pixels) were located perpendicularly to each other behind the badminton court and were positioned such that the back of the receiving player could be filmed out of two perspectives. A spherical reflective marker was attached to the back of the receiving player in the middle of the spine at the height of the fifth lumbar vertebra. This marker was used to track the velocity of the participant´s center of mass movements when receiving the service (s. figure 1).

Study Design and Implementation

The tests in elite badminton for group “A-national” and “B-national” were conducted on badminton courts of regular size in the German national training centers in Mülheim/Ruhr and Saarbrücken. During one series of trials, four athletes were engaged on the court: one serving player, one receiving player, and the double partners of these two players to complete the double teams and to provide competition-like conditions (figure 2).

Figure 1. Female elite badminton player while receiving a service offensively.

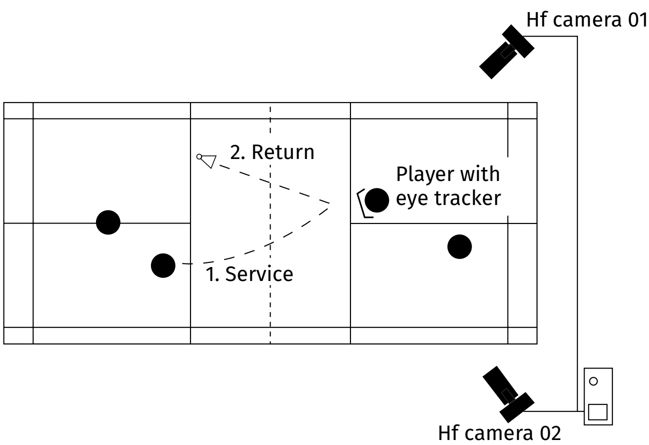

Figure 2. Experimental setup.

The recorded subject was equipped with the eye tracker and was instructed to return every service in an offensive manner by moving to the shuttle as quickly as possible. Every kind of service, a short (low) serve or a flick serve (high and long), was allowed, so that the subject had to react to these two stimuli like in an ordinary doubles competition (figure 3).

After the return, the rally was continued until a point was made to ensure natural test conditions. The subjects' eye movements were recorded over the whole series, while only the kinematics of the service and service return were captured by the high frequency cameras. Using this procedure, each subject executed 24 trails on average.

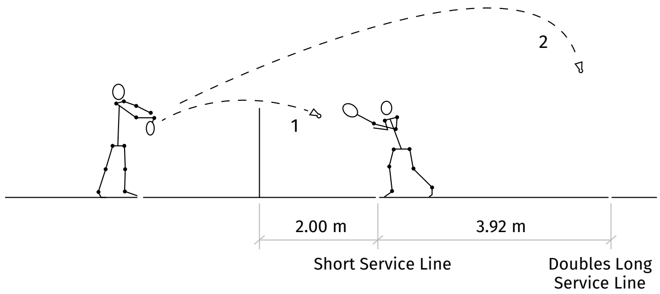

Figure 3. Trajectory of the short serve (1) and flick serve (2) in doubles.

Including the execution of long services in the experimental setup is necessary to provide an experimental setup similar to competition conditions. However, as frequency and relevance of flick serves in elite badminton is low (Gawin et al., 2013), this study only evaluated returns following a short service. This assured standardization of the results.

The measurements for the non-professional players took place in their respective training venues and were conducted the same way as for the professional players The only exception was that the kinematics was not recorded for the non-professionals because this project had to be concentrated on the performance of elite athletes.

Gaze and Performance Variables

Gaze strategies

Divergent from many studies listed above, gaze orientation in this project was measured frame by frame in the time interval of one second before action. The intention was to reveal a gaze strategy that included all eye events during the second before action, and not only the mere fixations, as gaze strategy also comprises the searching movements to identify regions of interest. Moreover, during gaze fixation, slow movements of the gaze axes are possible and likely to happen in the specific slow-paced situation in this study. The result is that gaze regions can change within one fixation. For example, gaze direction can move from the shuttle to the racket and to the trunk of the player within one fixation. Therefore, we expected to gain additional details of athletes' gaze strategies using this method, instead of only recording the gaze direction of the final fixations. Another reason for the application of frame by frame analysis instead of interpreting the final fixations was the outcome of earlier studies by the authors of this paper (e. g., Gawin et al., 2017; Zwingmann et al., 2017). The QE durations of some players differed more than 100 % when repeating the experiment under the same conditions and the appearance of final fixations seemed to be more closely related to the eye tracker´s detection algorithm than to specifically adopted gaze behavior. Therefore, the eye tracker video files were evaluated frame by frame for the second before the server´s racket made contact with the shuttle. In this time interval, the specific regions of gaze focus were recorded (s. table 1). The result was a pattern of gaze movements of the individual player during the second before the start of his reaction to the action of the serving player. For the analysis of gaze direction, the eye tracker videos were exported from the eye tracker software (beGaze, SMI, Paris, France) to an avi-format and were then visualized and evaluated in the software Kinovea.

Table 1.
Categories: Regions of gaze direction.

Variable	Definition
"Central"	The gaze is directed at the shuttle, the racket, or the shuttle (=left) hand (Racket/Shuttle/Left Hand). Note: the racket hand is quite distant from this central region.
"Upper Body"	The gaze is directed at the head, the neck the trunk, or the arms.
"Lower Body"	The gaze is directed at the hips or the legs.
"Unspecific"	The gaze is directed at a region that does not meet one of the specifications above. When "unspecific", the gaze is usually aimed at a region just beside the opposing player or the wall behind the court.

Kinematics

The velocity of the player´s starting movement towards the service served as the indicator for performance. This value was calculated by recording the point of time when the server's racket made contact with the shuttle and the time event when the subject's body reached a velocity threshold of 2 m/s (t_v2.0, figure 4). Therefore, this variable comprised the time for information intake, information processing, and the motor response. It expressed how fast the subject is capable of adapting his motor reaction to the specific stimulus. For this variable, the velocity of the marker attached to the back of the subjects was calculated using the three-dimensional video data from the high frequency cameras. The 3D coordinates of this marker were manually determined frame by frame by using the software Simi Motion (Simi Reality Motion Systems GmbH, Unterschleißheim, Germany), and the velocity-time-curves were smoothed by the moving average with a window size of five frames to compute the threshold of 2 m/s.

Statistics

The data for the regions of gaze direction consist of absolute and relative frequencies. Therefore, the differences in gaze patterns between the different skill groups were analyzed using a χ^2 test (SPSS version 26). In order to determine, which cells contribute to the differences between groups, standardized residuals of the contingency tables were analyzed (Sheskin, 2003).

To assess the correlation between gaze direction and performance, R (R Core Team, 2012) and lme4 were used (Bates et al., 2014). A linear mixed effect model was established with the fixed effect of gaze direction. Repeated measurements required the subject ID to be included as a random effect.

The visual inspection of the residual plots did not show any obvious heteroscedasticity or violations of residuals' normal distribution within the model. Statistical significance of model effects was evaluated by performing a likelihood ratio test of the full model against the null model without the fixed effect gaze direction. Alpha was set to .05.

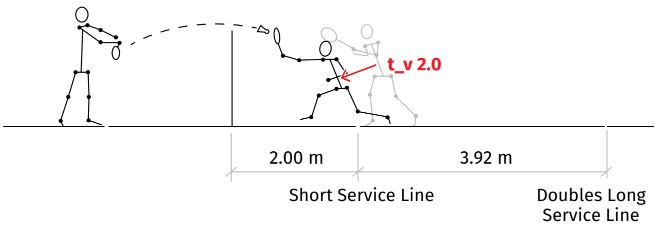

Figure 4. The performance variable t_v2.0, which is the velocity of the player´s reaction to the service.

RESULTS

Differences in gaze behavior of professional and non-professional players

The region that was focused on most frequently, was the "central" region (racket head, shuttle, and left hand. The left hand here is defined as the hand that holds the shuttle). The differences between the groups were most obvious in this category. The higher the performance level of the athletes, the more frequently they directed their gaze to this central region. Another obvious difference was found in the category upper body. The non-professional players tended to focus on the upper body (head, trunk, shoulders, and arms) more than the professional players. Remarkably, some subjects in the group of the non-professionals even kept their gaze steady on the opponent's face during the entire situation. Among all playing levels, the lower body (hip and legs) region seems to be less relevant than the other recorded regions of interest.

Although the frequency was zero for every group, the category "racket side hand" is displayed in the figure above to illustrate the contrast to Alder et al., (2014). Carefully interpreting the results of Alder and colleagues (2014), they detected a final fixation of this region in more than 20 % of all trials on average in professional players. In the current study, none of the players, neither professional nor non-professional, focused on this location.

The differences between the three groups in this study appear to be significant with a small effect (χ^2 [6] = 4801.97, p < .01, Cramers V = .24). The post hoc analysis of the standardized residuals of each contingency table's cell are depicted in table 2.

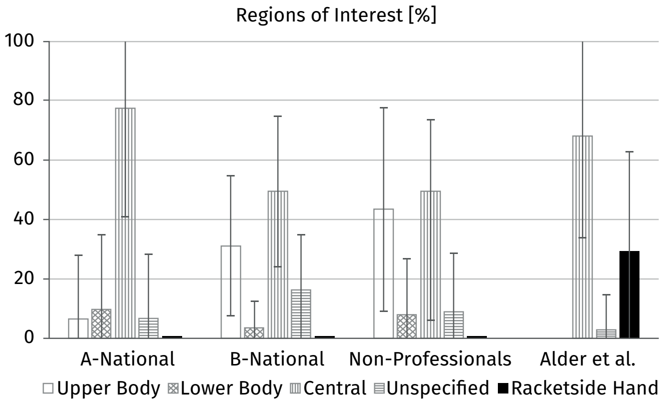

Figure 5. The regions that were focused on (error bars 95% confidence intervals).

Table 2.
Standardized residuals and p-values of each cell.

Categories		Expertise		
		A-National	B-National	Club Players
Upper Body	Frequency	522	6590	5899
	Expected Frequency	2432.7	6441.4	4136.9
	%	4.00%	50.60%	45.30%
	Standardized Resid.	-51.5	3.1	39.8
	p-values	0.000	0.002	0.000
Lower Body	Frequency	760	712	1098
	Expected Frequency	480.5	1272.3	817.1
	%	29.60%	27.70%	42.70%
	Standardized Resid.	14.6	-22.8	12.3
	p-values	0.000	0.000	0.000
Central	Frequency	6200	10468	5403
	Expected Frequency	4126.7	10926.8	7017.6
	%	28.10%	47.40%	24.50%
	Standardized Resid.	51.4	-8.9	-33.5
	p-values	0.000	0.000	0.000
Unspecified	Frequency	526	3434	1218
	Expected Frequency	968.1	2563.5	1646.4
	%	10.20%	66.30%	23.50%
	Standardized Resid.	-16.8	25.8	-13.6
	p-values	0.000	0.000	0.000

The analysis of the residuals show the lowest value for the category "upper body" in the group of the B-National players (s. table 2). But nevertheless all depicted p-values are below .05 and therefore all cells contribute to a significant outcome concerning the differences between groups.

Correlation between gaze direction and performance in service return in professional players

One result of the first part of this study was that professional badminton players (A-national and B-national group) tended to direct their gaze on the central region, comprising shuttle, racket head, and left hand, more frequently than less expert players (non-professional group). We hypothesized that any differences in gaze regions found between the professional and non-professional players could be considered advantageous for the professional players, which in turn would result in better performance in returning the service. Consequently, we suggested that such gaze behavior – enhanced focus frequency on the central region – would have a positive impact on specific performance. For this reason, we examined the correlation between gaze direction – expressed by the region "central" – and players' performance in returning the service.

The velocity of a player's motor reaction to the service (t_v2.0, see figure 6) was used to differentiate specific performance.

On average, the male players required about 270 milliseconds to reach the threshold velocity of 2.0 m/s when initiating service return. They acted about 60 milliseconds faster than the female players (s. figure 6).

The gaze strategy of focusing on the central region appeared to have no significant correlation with t_v2.0 in any of the players (females: χ^2 [1] = 1.604, p = .21; males: χ^2 [1] = .040, p = .84).

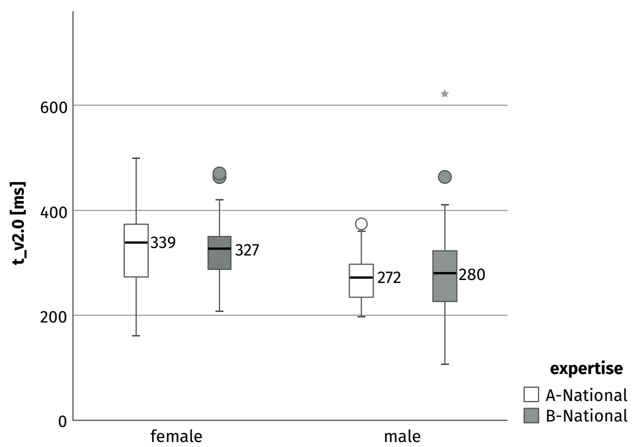

Figure 6. Players' motor reaction time to the service (t_v2.0) for the female and male elite players.

DISCUSSION

Gaze direction

Based on literature about eye tracking in racket sports, we expected to find that highly skilled players focus more frequently on distal segments of the moving opponent, such as the playing side arm, racket and wrist, and less expert players would tend to direct their gaze towards the shuttle. Our results cannot confirm this hypothesis. The observed gaze behavior of the different skill groups in this study turned out to be just the opposite. The higher the player's level, the more frequently they directed their gaze to the central region – comprising shuttle, racket head, and shuttle hand. Some of the former Olympic participants even focused on the shuttle for 100% of the recorded time. There are presumably expertise dependent gaze strategies in this game situation. It can be concluded that gaze behavior of top badminton players in the service situation is characterized by almost constant focus on the shuttle and the nearby regions. In the non-professional players the frequency of focus on the central region decreases significantly. The gaze focus of non-professional players seems to be towards the more peripheral regions, such as arm, upper body and face.

Alder and colleagues (2014) also examined the service situation, providing a comparable experimental setup with the exception that 2D-videos served as stimulus and that the players' response included a movement towards the anticipated virtual point of contact and a verbal statement concerning the shuttle's trajectory, not the specific motor response. The racket-side wrist – the hand that holds the grip of the racket – was a region where the players fixated their gaze in more than about 20% of all trials in that study. In our study, no participant focused on the racket-side hand or wrist. Moreover, the participants in this study rarely directed their gaze to the racket-side, the racket arm, or racket shoulder, of their opponents. The results in this study were obtained by recording the gaze behavior of athletes in a game situation with real opponents that came very close to the conditions in a real competition, especially, when considering stimulus and applied motor response. Therefore, it can be concluded that the research conditions are likely to have an influence on the obtained results. Apparently, even, or particularly, expert players use other visual search strategies when confronted with a two-dimensional stimulus on a video screen than when observing a real opponent.

The results in this study support one important outcome from Hüttermann and colleagues (2018) and from Klostermann et al., (2020) concerning ecological validity and representativeness of the experimental situation. They concluded that the transfer of results and practical implications from laboratory-based studies can be conflicted by unnatural research conditions.

The correlation between gaze direction and service return performance in professional players

To analyze the impact of gaze direction on performance, the parameter "velocity of the motor reaction" (t_v2.0) was defined and measured in this study. This parameter should reflect the complete reaction, beginning with the perception of the opponent´s service, information processing, and the movement towards the shuttle. In preparation of the study, this performance parameter was discussed with the German national coaches and subsequently established on the assumption that a badminton player in the doubles disciplines usually intends to travel to the shuttle as fast as possible after recognizing the kind of the service.

Next, because the most-skilled players focus on the central region - shuttle, racket head, and shuttle hand - more frequently than less-skilled badminton players, it seemed plausible that frequent focus on this region would lead to a shorter time for the motor reaction in the analyzed experienced players. This hypothesis could not be confirmed. The established linear mixed effect model did not show a significant correlation between gaze behavior and the velocity of the motor reaction in any of the participants.

The purpose of this model was to reveal the correlation between gaze strategy and a kinematic performance parameter that would reliably reflect player performance in the game situation "service return in doubles". However, this reduction apparently neglects further impact factors on the success in this specific situation. It is most likely that gaze direction itself cannot explain the superior performance of elite badminton players.

Conclusions and practical implications

The comparison of the different skill groups in this study revealed that athletes competing at high and at the highest levels of expertise utilize gaze strategies divergent from less experienced athletes. The elite players tend to anchor their gaze at the central region - shuttle, racket and racket hand. They concentrate their attention on this region, do not show fast eye movements and seem to be less distracted by peripheral stimuli. It is likely that this behavior also provides an efficient strategy for players with lower expertise and can serve as a reference. Basically, to improve specific performance in the service situation competition-like on-court drills that include additional perceptional tasks are advantageous for athletes of all skill levels. Many studies about visual perception in sports provide evidence for improvements in gaze behavior through training interventions, e. g., in golf (Moore et al., 2012; Vine et al., 2011), soccer (Wood & Wilson, 2011), basketball (Harle & Vickers, 2001; Oudejans et al., 2005), Ice-hockey (Mitroff et al., 2013), volleyball (Adolphe et al., 1997), and badminton (Hülsdünker et al., 2020a, 2020b; Hülsdünker et al., 2019). These studies show that specific training of visual perception was not only effective in changing gaze strategies, but also enhanced performance. Literature suggests the conclusion that on-court training of service situations involving additional perception tasks and applying methods that guide attention of the returning player implicitly can be beneficial. This can be achieved using specifically marked shuttles with colored dots, stripes or varying symbols (figure 7).

The receiving player has to recognize and name the color of the upper dot on the shuttle's surface immediately before the server has to execute the service. By this method the returning player is unconsciously forced to directly focus on the central region comprising shuttle and racket head.

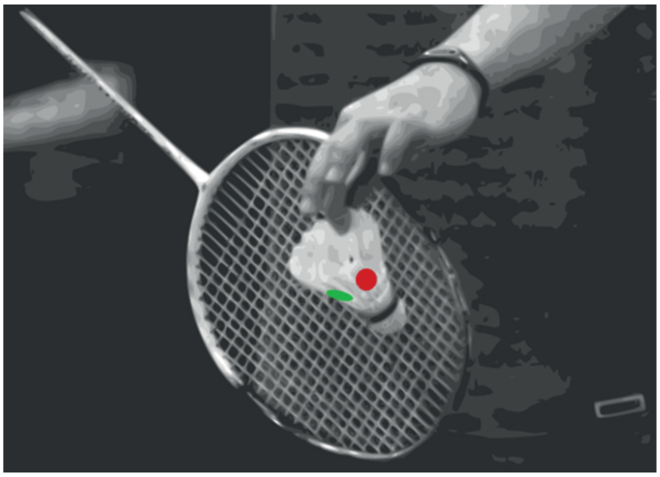

Figure 7. Colored marked shuttles as device for training of visual attention (image source: own lab).

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